Injection-Molded Thermoplastic Foams for Sound Insulation

By

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A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy

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Abstract

Open-cell foam materials have many applications such as sound and thermal insulators, filter and separation membranes, scaffolds, battery electrode supports, and printing heads. Commercial open-cell polymeric foams have been almost exclusively manufactured with polyurethane thermoset materials. While the production of thermoplastic open-cell foam has been studied in batch foaming and extrusion systems, open-cell foaming with the injection molding process has not received enough attention due to its inherent challenge to produce an open-cell structure. However, despite that challenge, injection molding is one of the most cost-effective and widely used polymer processing technologies. Thermoplastic polymeric open-cell foams that are environmentally friendly and recyclable were developed for different applications including sound insulation using the injection molding machine process. This thesis work combines the conventional foam injection-molding process with mold opening and gas counter pressure techniques to achieve highly-expanded open-cell foam structures with/without an air-gap for sound insulation. Environmentally friendly and recyclable foams produced in this study showed promising results for sound insulation and sound absorption.
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$A$</td>
<td>Area</td>
</tr>
<tr>
<td>$A_{per}$</td>
<td>Perforation area</td>
</tr>
<tr>
<td>$B$</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>$BA$</td>
<td>Blowing agent</td>
</tr>
<tr>
<td>$C$</td>
<td>Speed of sound wave propagation</td>
</tr>
<tr>
<td>$C.C.$</td>
<td>Closed-cell content</td>
</tr>
<tr>
<td>$C_0$</td>
<td>Sound velocity</td>
</tr>
<tr>
<td>$CO2$</td>
<td>Carbone dioxide</td>
</tr>
<tr>
<td>$GCP$</td>
<td>gas counter-pressure</td>
</tr>
<tr>
<td>$I_1$</td>
<td>Sound intensity before hitting the wall</td>
</tr>
<tr>
<td>$I_2$</td>
<td>Sound intensity after passing the wall</td>
</tr>
<tr>
<td>$M$</td>
<td>Molecular weight</td>
</tr>
<tr>
<td>$MPP$</td>
<td>Micro-perforated panels</td>
</tr>
<tr>
<td>$O.C.$</td>
<td>Open-cell content</td>
</tr>
<tr>
<td>$PC$</td>
<td>Polycarbonate</td>
</tr>
<tr>
<td>$P_{rms}$</td>
<td>Amplitude of pressure changes described by the root-mean-square amplitude</td>
</tr>
<tr>
<td>$P_M$</td>
<td>Maximum pressure amplitude</td>
</tr>
<tr>
<td>$PP$</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>$R$</td>
<td>Reflection coefficient</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Surface resistance</td>
</tr>
<tr>
<td>$R_u$</td>
<td>Universal gas constant</td>
</tr>
<tr>
<td>$SEM$</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>$TC$</td>
<td>Temperature controller</td>
</tr>
<tr>
<td>$T_k$</td>
<td>Temperature in kelvin</td>
</tr>
<tr>
<td>$TL$</td>
<td>Transmission loss</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Temperature of the medium</td>
</tr>
<tr>
<td>$TPS$</td>
<td>Transient plane source</td>
</tr>
<tr>
<td>$V_a$</td>
<td>Volume of the open and interconnected cells</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Volume of empty sample chamber</td>
</tr>
<tr>
<td>$V_{cav}$</td>
<td>Volume of the backing cavity</td>
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<tr>
<td>$V_r$</td>
<td>Volume of reference chamber</td>
</tr>
<tr>
<td>$V_s$</td>
<td>Volume in sample chamber</td>
</tr>
<tr>
<td>$V_t$</td>
<td>Total volume of material</td>
</tr>
<tr>
<td>$Z$</td>
<td>Impedance</td>
</tr>
<tr>
<td>$Z_B$</td>
<td>Normal surface impedance</td>
</tr>
<tr>
<td>$Z_c$</td>
<td>Characteristic impedance</td>
</tr>
<tr>
<td>$Z_r$</td>
<td>Reflection impedance</td>
</tr>
<tr>
<td>$Z_0$</td>
<td>Impedance of the fluid domain</td>
</tr>
<tr>
<td>$Z_n$</td>
<td>Normal surface impedance</td>
</tr>
<tr>
<td>$d$</td>
<td>Thickness</td>
</tr>
<tr>
<td>$dB$</td>
<td>Sound power</td>
</tr>
<tr>
<td>$d_f$</td>
<td>Density of foam</td>
</tr>
</tbody>
</table>


\( d_s \)  
Density of solid (unfoamed)

\( f \)  
Frequency

\( k \)  
Wave number

\( n \)  
Number of the cells

\( p \)  
Pressure

\( v \)  
Velocity

\( v_f \)  
Void fraction

\( s \)  
Perforation ratio

\( w \)  
Width

\( c' \)  
Numerical coefficient

\( E' \)  
Incident energy flux

\( a_\infty \)  
Tortuosity

\( \alpha \)  
Absorption coefficient

\( \varepsilon_e \)  
Added length

\( \lambda \)  
Wave length

\( \lambda_{gas} \)  
Conductivity of nitrogen gas

\( \lambda_{matrix} \)  
Conductivity of matrix

\( \nu \)  
Ratio of specific heats

\( \varphi(x,t) \)  
Displacement of a linear wave

\( \rho \)  
Density

\( \omega \)  
Angular frequency

\( \rho_s \)  
Density of the solid unfoamed

\( \rho_f \)  
Density of foam

\( \rho_0 \)  
Density of sound

\( \phi \)  
Expansion ratio

\( \sigma \)  
Air flow resistivity

\( \Lambda \)  
Viscous characteristic length

\( \Lambda' \)  
Thermal characteristic length

\( \eta \)  
Viscosity of the air

\( \dot{\eta} \)  
Dynamic viscosity of the air

\( \zeta \)  
Tortuosity factor
Chapter 1: Introduction and Background

1.1. Preamble

Recently, sound insulation has received increasing interest due to the serious noise pollution in our living environment. Various strategies and sound insulation systems have been developed, but most of them are expensive due to either the complexity of the systems or material cost. Open-cell (or porous) materials are commonly used for sound insulation, but most of the materials used are not recyclable. An example is the use of polyurethane open-cell foams in the sound insulation systems of automobiles. Due to economical foaming processes and lower prices of polymer, new structures can be developed for industrial and also home usage. Polymer based sound absorption structures are lower in weight and show reasonable acoustic properties, which can replace many of the existing structures.
1.2. Acoustic and Noise Control Engineering

Acoustics is the art and science of understanding sound and its interaction with the physical world. In acoustic and noise control engineering, the main goal is to reduce or eliminate the noise power, whether outdoors or indoors. Noise control is an important aspect in transportation, architectural design, urban planning, and so on. For instance, the use of hybrid vehicles not only helps reduce air pollution and fuel consumption, but also decreases roadway noise significantly. In architectural design, an example of good auditorium design will be able to reduce the reverberation (echo) extensively to increase the quality of speech. The World Health Organization (WHO) recently announced that every third person in the European region is suffering from health-related issues due to noise pollution. The range of frequency humans can hear is between 20 Hz and 20 KHz. The frequency range of the noise that people face in their daily life is 50 Hz - 5000 Hz, as shown in Figure 1.1. Most of the noise produced from domestic devices in everyday life are in the lower-end of the frequency range of 500-1500 Hz. This is the main reason scientists are trying to develop high efficient insulating materials for low-frequency spectrum noise.

![Figure 1.1: Audible sound and noise frequency ranges.](image-url)
1.3. Foam Materials

Foam materials can be open-cell or closed-cell and they are quite different in terms of their manufacturing and applications. In a foam structure, if cells are interconnected and are open to the surface of the structure, the structure is called porous or open-cell. Open cell structures permit the flow of a liquid or gas medium through the interconnected cellular structure of the foam without destroying the foam structure [1-2]. Figure 1.2 shows a foam material with open-cell and closed-cell structures.

Figure 1.2 A foam material with open-cell and closed-cell structures [2].
Open-cell foams usually have a high expansion ratio and they are mostly flexible material. One of the general applications is the packaging and shipping of fragile objects [3]. The interconnection of the voids in open-cell foams and their low weight make these foams the most suitable foam for some applications such as sound insulation, packaging, scaffolds, and printer applications. Unlike open-cell foams, closed-cell foams are usually rigid. Most of the cells in the closed-cell foams are not interconnected and fluid cannot penetrate through the structure. Closed-cell foams can have a variety of hardness and density [4]. Sometimes, a physical rupture of the closed cells can be considered as a viable method for opening the cells [5].

The choice of using open-cell or closed cell foams varies depending on their characteristics and applications. As an example, both types of foam are commonly used in building applications. Open-cell foams would usually not be used for thermal insulation in humid places within a building where they could absorb water. The presence of the absorbed water would significantly reduce the thermal performance because water is a poor insulator compared to air. In contrast, closed-cell foams would be a good choice for thermal insulation in humid places. The cell size, cell density, porosity (for open-cell foams), and expansion ratio are the main structural properties that govern the performance of each foam, and hence, they have to be studied prior to any applications.

Foam materials have revolutionized industry quite dramatically in recent years. The constant increase in the usage of these materials in airplane construction is one example of the importance of these materials in the replacement of other conventional materials. There are several reasons for the importance of foam material in industry, and the following are a few examples [6-7].
I. Foams are lightweight, waterproof, strong, inexpensive, easy to maintain, durable, and flexible.

II. It is possible for foam materials to be combined with conventional materials to make a required composite or sandwiched material of desirable specifications.

III. It is easy to be machined using inexpensive tools.

IV. It is easy to be formed or shaped into complex geometries like airfoils.

V. It facilitates very large bulk manufacturing.

1.4. Research Motivation

Currently, most noise control materials available are not environmentally friendly or recyclable. Polyurethane foams are commonly used as sound insulators [8–10]. But it is difficult to treat polyurethane foam waste. These foams are not easy to recycle cost-effectively and their incineration produces poisonous gas [11, 12]. Their low density and high volume means they easily become landfill. Glass wool has also been used as a sound insulator but only in an environment that is not regularly accessed by humans due to health concerns. Also, fiberglass is not considered a reliable acoustic controller due to its relatively high density and low processability [13]. Therefore, thermoplastic materials such as polypropylene would be a promising alternative to the currently available sound insulating materials [14].

Open-cell foams have shown promise for sound insulation across a wide range of frequencies [15, 16]. The interconnectivity of the cells allows air to flow through them. Air-flow
viscosity and the thermal conductivity of the foam are considered as the two main reasons for sound wave attenuation [17]. Nevertheless, to absorb low-frequency sound with conventional open-cell foams, a considerable foam thickness is required [18]. Multilayer acoustic foams [19, 20] constructed with an air gap are considered as promising solutions for low-frequency sound absorption (400–1600 Hz). In some applications, the front panels of these multilayer foams were perforated to enhance their acoustic behavior [21, 22]. The costs associated with multilayer acoustic foams are relatively high and, in most cases, the open-cell foams used in such insulators are not recyclable. It is thus of great value to develop cost-effective and recyclable alternatives to these insulators.

Manufacturing open-cell foams using the foam injection molding process is of great interest to industry. This is due to their reliability, availability and cost-effectiveness. Producing open-cell injection-molded foams is, however, challenging and has received very little attention. Since foaming takes place in an enclosed mold cavity, the range of achievable void fractions and cell densities is limited in the foam injection-molding process [23, 24]. Therefore, foam injection-molding strategies should be developed in order to achieve highly expanded open-cell foams.

1.5. Problem Statement and Objectives

The main objective of this thesis is to produce thermoplastic injection molded foams for sound insulation. Currently, sound insulating materials are exclusively produced using thermoset polyurethane materials. In this work, the development of environmentally friendly and recyclable acoustic materials, which can replace current non-environment-friendly acoustic material, is intended. Throughout this development, injection molding, which is commercially available for
the industry, was utilized to produce open-cell acoustic foams. In order to achieve this long-term plan, efforts were made to achieve the following short-term goals:

I. Study the effect of manufacturing parameters of thermoplastic foams on their sound insulation behavior.

II. Develop a methodology to produce environmentally friendly recyclable open-cell acoustic foam using the injection molding process.

III. Apply available techniques such as integrating air-gaps and perforated panels with thermoplastic foams for improving the sound insulation behavior.

1.6. Organization of Thesis

This thesis is organized into 8 chapters. Chapter 1 presents an introduction to foams, acoustics, and noise control. It also includes the motivation, objective, and overview of the thesis.

Chapter 2 presents the literature and theoretical background on the development and simulation of acoustic foams. The fundamentals of acoustics, open-cell foam, characterization, and modeling are discussed in this chapter. It also includes different models including analytical, empirical, and semi-empirical models used in sound absorption prediction.

Chapter 3 explains the development of acoustic thermoplastic porous foams in batch foaming. Also it describes the effect of pore size, porosity, and air-gap in the acoustic behavior of batch foaming samples.
Chapter 4 presents a novel strategy for producing open-cell foam using the injection molding process. The process and experimental setup for the development of highly expanded foams are presented. Also, the results of acoustic, thermal, and mechanical characterization of the developed foams are presented in this chapter.

In Chapter 5, the development of air-gap integrated acoustic foams for low frequency noise insulation is demonstrated. The experimental setup and process that were developed for producing 5-layer acoustic foams are explained. Furthermore, the effect of each layer of the developed foam and skin layer perforation on the acoustic behavior of the developed foam is studied.

A novel approach to the development of high-performance micro perforated panels (MPPs) for low frequency absorption is presented in Chapter 6. Also, the inherent challenges for foaming thin-walled injection parts are explained and strategies used for producing uniform foam thin-walled injection molded parts are presented.

In Chapter 7, a formula is developed to estimate the transmission loss of injection molded open-cell foams. The effect of material on the transmission loss of injection molded samples is discussed. Finally, a summary and conclusion for the major contributions along with recommendations for future research are presented in Chapter 8.

1.7. References


Chapter 2: Development and Simulation of Acoustic Materials

2.1. Fundamentals of Acoustics

2.1.1 Definition of Sound Wave

Sound (or noise) is created when pressure variations or oscillations in an elastic medium take place. The elastic medium can be a gaseous, liquid, or solid phase. In most cases for sound, air is the elastic medium. Sound wave propagates in the air longitudinally by rarefactions and compressions of the air molecules and it propagates until its power dissipate. Figure 2.1 shows propagation of the sound wave in the air medium.
A sound wave is characterized by the amplitude of the pressure change, wavelength, and frequency. The amplitude of the pressure changes is described by the root-mean-square amplitude \( (P_{rms}) \) in which the instantaneous sound pressures are squared, averaged and the squared root of the average is taken. Sound pressure amplitude is also characterized in terms of the maximum pressure amplitude \( (P_M) \) in Pascal. Eq.2.1 shows the governing equation between the maximum pressure amplitude and the root-mean-square amplitude for a sound wave.

\[
(P_{rms}) = 0.707 (P_M)
\]  

(2.1)

The speed of sound wave propagation, \( C \) in m/s, is related to the frequency in 1/s and wavelength (\( \lambda \)) in m as
By an increase in the temperature of the medium (T_{ms}) in Celsius, the speed of the sound wave also increases and Eq.2.3 can be used to calculate the speed of the sound wave in different medium temperatures.

\[ C = 332 + 0.6 T_{\text{me}} \]  \hspace{1cm} (2.3)

For gaseous phases, the velocity of the sound wave can be calculated using Eq.2.4 equation: in which \( T_k \) is the temperature in kelvin, \( R_u \) is the universal gas constant in Joule/molK, \( \gamma \) is the ratio of specific heats, and \( M \) is the molecular weight in kg/mol.

\[ C = \sqrt{\gamma R_u \frac{T_k}{M}} \]  \hspace{1cm} (2.4)

### 2.1.2. Sound Wave Power

Sound power is calculated using a reference sound pressure \( P_{\text{ref}} = 20 \mu \text{Pa} \) (see ISO 3744, ISO 9614). This value is the root-mean-square amplitude of the minimum acoustic power audible to a young and healthy human ear. The following is the expression used to calculate the sound power (dB) using the reference pressure.

\[ dB = 10 \log_{10} \frac{\text{sound pressure}}{\text{reference sound pressure}} \]  \hspace{1cm} (2.5)

The median hearing threshold is about 5 dB (at 1 kHz). The pressure at which sound becomes painful is called the pain threshold pressure. The pain threshold pressure for sound will
vary with frequency and is age-dependent. In the literature, sound above 120 dB is normally considered the pain threshold pressure level of a typical adult.

2.2. Acoustic Materials

Acoustic materials, depending on their components, manufacturing process and properties, are classified into four groups: fibrous materials, perforated panels, granular materials, and polymer foam materials. Glass, mineral wools, and felts are considered fibrous material, which are commonly used for sound insulation [1]. Perforated panels are constructed with a thin perforated panel and an air cavity, and are used only when the absorption of sound energy is required. In most architectural rooms, perforated panels are used to absorb the noise and attenuate the reflected sound (echo). Granular or chip-type materials are used for sound insulation. Conventional granular insulating materials consist of light-weight materials. Granular materials have an average grain diameter of about 1.5 millimeters [1]. Finally, using foam material for sound insulation is the most common insulating method in the industry. More information about these sound insulating materials is given in the next section.

2.3. Acoustic Open Cell Foams

Unlike closed-cell foams, open-cell foams are commonly used for sound insulation. Air molecules, which convey the energy of the sound wave, can easily penetrate inside the open-cell foams. When air is passing through these porous materials, it faces resistance from the surface of the pores because of friction. This friction generates heat and will be dissipated to the other parts of the porous material and air. In the case that the intersection of the pores changes, air will experience compression and decompression and this can be another reason for sound energy
attenuation while it passes through open porous materials. Viscosity and thermal conduction are two main reasons for sound absorption in open-porous materials.

2.4. Bulk Modulus and Characteristic Impedance of the Air

Bulk modulus and characteristic impedance are the two primary parameters that are discussed in sound insulation. Below, a brief explanation of these two parameters is provided.

The displacement of a linear wave in a compressible lossless fluid can be calculated using the following equation

$$\varphi(x,t) = \frac{A}{\rho_0 a^2} \exp[j(\omega t - kx)] \quad (2.6)$$

in which $\omega$ is the angular frequency in rad/second and $k$ the wave number in 1/meter. The wave number can be calculated by

$$k = \omega (\frac{\rho}{K})^{1/2} \quad (2.7)$$

in which $\rho$ and $K$ are the density in kg/m$^3$ and the bulk modulus of the air in Pa, respectively. The bulk modulus of a substance measures the substance’s resistance to uniform compression. The speed of sound in air and other gases, liquids, and solids is predicted by the density and elastic properties of these medium (bulk modulus). If the fluid is perfectly elastic with no damping, $k$ is a real number.

For a planar sound wave, the pressure and the velocity are related by:
\[ v_x(x, t) = \frac{1}{z_c} p(x, t) \]  

(2.8)

and

\[ Z_c = (\rho K)^{1/2}. \]  

(2.9)

in which \( Z_c \) is the characteristic impedance of the fluid in \( \text{Pam}^{-1}\text{S} \). Impedance is also defined as the ratio of the pressure to the volume displacement at a given surface in a sound-transmitting medium. For air at the temperature, pressure, and density of 18°C, 103.3kPa, and 1.213 kgm\(^{-3}\) the characteristic impedance and bulk modulus are 415.1 Pam\(^{-1}\)S, and 1.42 x 10\(^5\)Pa, respectively. The impedance \( Z \) of a wave during traveling is decreased. The following equation can be used to calculate the impedance of a wave after traveling having an impedance of \( Z_1 \).

\[ Z_2 = Z_c \frac{-jZ_1 \cot g \ kd + Z_c}{Z_1 - jZ_c \cot g \ kd} \]  

(2.10)

Furthermore, when a sound wave passes through a fluid with a thickness of \( d \) and reflects back after it hits an impervious wall, the impedance can be calculated using the following equation.

\[ Z_r = -jZ_c \cot g \ kd. \]  

(2.11)

### 2.5. Important Parameters in Sound Insulation

Reflection coefficient, absorption coefficient, and acoustic impedance are three important parameters in sound insulation. Below, a short explanation for each of these parameters is given.
Reflection coefficient ($R$): A sound wave will experience partial transmittance and partial reflectance when the medium through which it travels suddenly changes. The sound reflection coefficient of a material $R$ is the ratio of outgoing sound wave pressure $P'$ to incoming sound wave pressure $P$.

$$R = \frac{P'}{P} \quad (2.12)$$

The measurement for the sound pressure while hitting a layer of material is performed with a rigid plate, being placed on the back of the sample to block the transmission of the sound wave, as shown in Figure 2.2.

**Figure 2.2: Incoming and outgoing sound wave pressures while hitting a layer of material backed with a rigid wall.**
The equation for the reflection coefficient can be rewritten using the characteristic impedance of air

\[ R = \frac{Z - Z_c}{Z + Z_c} \]  

(2.13)

in which \( Z \) and \( Z_c \) are the surface impedance and characteristic impedance of the air, respectively. In case there is no change in the amplitude of incoming and outgoing waves, the reflection is 1. Furthermore, when the amplitude of the impedance is equal to zero or infinite this ratio would be 1 again.

Absorption coefficient (\( \alpha \)): The absorption coefficient is a basic quantity used in calculating the penetration of materials by quantum particles or other energy beams. It is a measure of absorption. Absorption coefficient in acoustics is used for quantifying the ability of a material in absorbing sound. Wallace Sabine was a pioneer in this concept. A unit named in his honor is Sabine. A Sabine is defined as a fraction of acoustic power absorbed by a 1 metre square of open window.

Absorption coefficient \( \alpha \) is related to reflection coefficient \( R \) as

\[ \alpha = 1 - R^2. \]  

(2.14)

The absorption coefficient is often used in architectural acoustics and this equation can be rewritten as

\[ \alpha = 1 - \frac{E'}{E} \]  

(2.15)
in which $E'$ and $E$ are the incident and reflected energy flux to and from the acoustic material, respectively.

Acoustic impedance ($Z$): Acoustic impedance is a frequency dependent parameter with the unit of Rayls. It can be calculated using the following equation.

$$Z = \frac{p}{\nu s}$$ (2.16)

in which $Z$ is acoustic impedance (Rayls), $p$ is the sound pressure, $\nu$ is particle velocity, and $s$ is the surface area, through which acoustic waves of particular frequency propagates. The results of calculated acoustic impedance for a range of excitation frequencies are normally represented in the form of an impedance curve.

2.6. Characterization of Acoustic Foams

2.6.1. Cell Morphology

The cell morphology for typical plastic foams can be characterized in terms of cell size, cell density, and cell size distribution. In some occasions, information such as cell-wall thickness, the structure of the cell-wall, interconnection of the cells are also studied. The cell morphology can be examined by using a scanning electron microscope (SEM). SEM is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. The cell size can be measured from the SEM micrographs with the aid of image J utility software. For the cell size characterization, the shortest and largest diagonals of the cell's circle
on SEMs, were averaged. The foam density ($\rho_f$) can be measured using the water-displacement method (ASTM: D792-08 http://www.astm.org/Standards/D792.htm). The cell density is obtained by counting the number of cells per unit area and using,

$$N = \left(\frac{n}{A}\right)^{3/2} \frac{\rho_s}{\rho_f}$$

(2.17)

where $n$ is the number of cells in the defined area $A$, $\rho_s$ is the density of the solid unfoamed polymer and $\rho_f$ is the density of the foamed polymer in kg/m$^3$.

### 2.6.2. Void Fraction and Expansion Ratio

The void fraction of a foam structure is the ratio of the volume of void to the entire volume of the foam. This can be calculated by measuring the density of material before and after foaming. The following equation defines this relationship:

$$\nu_f = \frac{d_f}{d_s}$$

(2.18)

The expansion ratio of foam is inversely related to the void fraction and can be calculated using this equation.

$$\Phi = \frac{d_s}{d_f}$$

(2.19)

The bulk density of solid and closed-cell foams can be measured by water immersion and observing water displacement. However, this technique may not be suitable for measuring the
foam density of open-cell foams because of its porous structure. One method to measure the density of open porous foams is the sample cutting in a geometric shape so that its dimensions can be easily measured for estimating its geometric volume.

2.6.3. Sound Insulation

An impedance tube is frequently used for measuring acoustic properties of a material. An impedance tube consists of a tube, a generator (or loud speaker), and two fixed microphones, as shown in Figure 2.3. A loud speaker at one end of the tube propagates plane waves (acoustic waves) in a variety of frequencies; the wave hits the test material which is placed at the other end of the tube. A portion of the created wave is absorbed by the test sample and the rest is reflected back, which can be sensed by microphones. Superposition of forward- and backward- travelling waves inside the tube is applied to create pressure maximum (antinode) and minimum pressure (node) points inside the tube.

Figure 2.4 shows the case of two interfering two waves in constructive and destructive situations. The ratio of the pressure maximum (antinode) to the minimum pressure (node) is used for identifying the Reflection coefficient ($R$), Absorption coefficient ($\alpha$), and Acoustic impedance ($Z$). The operating frequency of the impedance tube depends on the diameter of the tube and the spacing between the two microphone positions. This method is described in both ISO 10534-2 and ASTM E1050.
Figure 2.3: Schematic of simple impedance tube used for sound insulation measurement.

(a)
2.6.4. Porosity

Porosity is one of the most important quantities for describing the structure of the cells and it influences important physical and mechanical properties [1]. Various methods and standards have been developed for testing and characterizing porous structures. ASTM D 6226 is a test method for characterizing porosity, which is specialized for cellular plastic materials. Cells in polymer foams may be interconnecting (open cell), non-connecting (closed cell), or any combination of these types. To measure the porosity, the accessible cellular volume (i.e. the open-cell volume) of a material is measured. The remaining volume is considered as volume occupied by both the closed cells and cell walls. Open cell content (O.C.) of foam can be estimated using the following equation in which $V_a$ and $V_g$ are actual and geometric volumes of the foam respectively.

\[
O.C. = \left(1 - \frac{V_a}{V_g}\right) \times 100\% \tag{2.20}
\]
Also, closed cell content (C.C.) can be calculated using this equation after knowing the open-cell content (O.C.).

\[ C.C. = 100\% - O.C.\% \quad (2.21) \]

The porosity (\( \varnothing \)) of a material containing open cells is obtained by the ratio of the volume of the open and interconnected cells (\( V_o \)) to the geometric volume of material (\( V_g \)). Thus,

\[ \varnothing = \frac{V_o}{V_g} \quad (2.22) \]

In this equation, only the volume of air, which is not locked within the frame, must be considered in \( V_a \). For most fibrous materials and thermoset polyurethane foams, the porosity values are typically very close to 1. The method for measuring porosity is given in ASTM D 6226.

A gas pycnometer is a laboratory device used for measuring the actual density as well as the porosity of different materials including porous foam materials. The gas pycnometer essentially consists of two chambers, one to hold the sample and a second chamber, with known internal volume, as the reference volume. There is a valved pathway connecting the two chambers. Initially, gas which is usually nitrogen or helium flows to the sample chamber at a predetermined pressure, as assigned in the ASTM standard. Opening the valve in the pathway permits the flow of gas to the reference chamber, and after a short time, both chambers will have the same pressure. Through measuring the initial pressure in the sample chamber and the final pressure in both chambers, the volume occupied by the sample can be estimated. Below is the equation for calculation.
\[ V_s = V_c + \frac{V_r}{1 - \frac{P_1}{P_2}} \]  

(2.23)

In which \( V_s \) is the volume in a sample chamber, \( V_c \) is the volume of the empty sample chamber, \( V_r \) is the volume of the reference chamber, \( P_1 \) is the initial pressure in the sample chamber, and \( P_2 \) is the final pressure in both chambers.

2.6.5. Flow Resistivity

Resistivity of a porous material to airflow has a strong relation to its ability in acoustic absorption. This property is defined as the flow resistivity [1]. Figure 2.5 shows a schematic of the setup for measurement of the flow resistivity of a porous material.

![Figure 2.5: Schematic of flow resistivity measurement setup.](image)
The open porous material is placed in a pipe and due to the resistivity of the material, different pressures will be created at the two sides of the sample as the air flows. The pressure difference causes air to flow from the side with higher pressure to the lower pressure side. The flow rate will depend on the applied pressure difference and structure of the open porous material. Airflow resistivity is defined in ASME and the following is the equation for calculating this parameter.

\[ \sigma = \frac{(P1 - P2)}{Vh} \]  

(2.24)

In this equation, the quantities \( V \) and \( h \) are the mean flow of air per unit area of material in m\(^3\)/s and the thickness of the material, respectively. In MKSA units, flow resistivity is expressed in Nm\(^{-4}\) s. ASTM C522-87 provides a method for measuring airflow resistance of porous materials that can be used for the absorption and attenuation of sound. In this method materials cover a range from thick boards or blankets to thin mats, fabrics, papers, and screens. When the material is anisotropic, special consideration should be made for measurements along different axes of the specimen.

2.6.6. Tortuosity (\(a_{\infty}\))

The complexity of an open-cell network is described as tortuosity. This quantity represents the length of an open-cell network inside the open cell foam. Depending on the angle in which the incident sound wave enters the sample, the tortuosity value may also vary. For fibrous materials, when the propagation of the sound wave is parallel with the orientation of the fiber, the tortuosity is equal to one. For the case that there is an angle of (\(\Theta\)) between them, the tortuosity can be calculated using the following equation:
In the case that the porous material has a complex open-cell network, the tortuosity may reach as high as 3.

2.6.7. Viscous Characteristic Length ($\Lambda$)

Viscous characteristic length refers to the cells’ microscopic dimensions and represents the viscous loss of sound wave energy when the wave passes through the porous structure [2, 3]. Viscous characteristic length is more important in small cells. Viscous characteristic length is equal to twice the volume-to-wet-surface ratio of the open-cell network while it is weighted by the velocity in the volume and on the surface. The following is the equation to calculate viscous characteristic length.

$$\frac{2}{\Lambda} = \frac{\int_A v_i^2 dA}{\int_V v_i^2 dV}$$

in which $v_i$ represents the velocity of the sound in m/s; $A$ and $V$ are the area in m$^2$ and the volume of the pores in m$^3$ respectively. In practice, this parameter is measured indirectly using an impedance tube.

2.6.8. Thermal Characteristic Length ($\Lambda'$)

The thermal characteristic length refers to the cells’ microscopic dimensions and represents the thermal loss of sound wave energy when the wave passes through the porous structure [2, 4]. The thermal characteristic length is more important in large cells. This quantity is equal to twice
the volume-to-wet-surface ratio of the open-cells network and can be calculated using following equation,

\[
\frac{2}{\mathcal{N}} = \frac{\int_{A}dA}{\int_{V}dV} = \frac{A}{s}
\]  

(2.27)

In practice, the thermal characteristic length is measured indirectly using an impedance tube.

2.7. Approaches in Modeling Acoustic Foams

Many researchers, in the last few decades, developed models for estimating acoustic impedance of porous material, while others worked on improve model accuracy. In 1956, Biot developed a model to calculate the impedance of rigid framed materials [5]. Another model by Pride et al. was for attaining effective density and the simplified Lafarge model was for the bulk modulus [6]. The approach to the development of these models can be classified into analytical, and empirical (or semi-empirical).

2.7.1. Analytical Models

Craggs used a finite element method to estimate the acoustic impedance of porous materials [7]. He considered the porous material as a rigid body and defined an eight-note iso-parametric model for simulation. This approach was evaluated as a precise method for a one-dimensional propagation. But Tsay et al [7] tried to use a finite element method for three-dimensional propagation, but the estimation was far from the experimental results.
2.7.2. Empirical and Semi-Empirical Model for Impedance Simulation

Delany and Bazley [8] in 1970 presented semi-empirical formulations for estimating the impedance of porous materials. They assumed the air inside the porous medium as equivalent to a free fluid medium and tried to correlate the airflow resistivity of the porous material to the characteristic impedance ($Z_c$) and the wave-number ($k$) of the sound waves. The static airflow resistivity of the porous material is measured experimentally, and then the impedance is calculated. The following are the equations used in this model to calculate the impedance of porous material for a wide range of frequencies [7].

\[ Z_c = \rho_0 \cdot c_0 \cdot (1 + 0.0571X^{-0.754} - J0.087X^{-0.732}) \]  
(2.28)

\[ k = \frac{\omega}{c_0} \cdot (1 + 0.0978X^{-0.7} - J0.189X^{-0.595}) \]  
(2.29)

\[ X = \frac{\rho_0 f}{\sigma} \]  
(2.30)

In these formulations, $\rho_0$ and $c_0$ are the density in kg/m$^3$ and sound velocity in m/s, respectively. Further, $\sigma$, $f$ and $\omega$ represent the static airflow resistivity in Pa.s/m$^2$, frequency in s$^{-1}$, and angular frequency in rad/s. This method correlates only airflow resistivity to the impedance, and airflow resistivity is a one-dimensional characteristic of the material while the sound wave propagates three dimensionally. This created difficulties with estimating the impedance of anisotropic materials such as fibrous material. Further, researchers discovered that there is more than one parameter affecting the impedance.
As an example of later efforts to improve the accuracy of the impedance estimation by considering additional relevant structural parameters of the materials, Johnson et al. (1987) introduced the “tortuosity” parameter \( a_\infty \) in his model. The effective density of the fluid in his model is defined as:

\[
\rho = a_\infty \rho_0
\]  

(2.31)

in which \( a_\infty \) is the tortuosity and \( \rho_0 \) is the density of the fluid. The minimum value for tortuosity is one when the voids are straight cylindrical holes. For porous foam material, usually this parameter is bigger than one.

Gardner [9] used artificial neural networks (ANN) in his empirical model to estimate the impedance of acoustic materials with higher accuracy. In his model, the surface acoustic impedance, normal incidence absorption coefficient, and the static flow resistivity of the foams were measured, and this data was then used to estimate the acoustic impedance of the foams.

The Johnson-Allard model is one of the most adapted models currently used for the estimation of sound insulating materials. This model was developed in 1994 and it describes the impedance of the sound wave in a rigid frame air-saturated porous medium with five macroscopic quantities: porosity (\( \phi \)), airflow resistivity (\( \sigma \)), tortuosity (\( a_\infty \)), and viscous and thermal characteristic lengths (\( \Lambda \) and \( \Lambda' \)). This model correlates these five parameters to the effective density and effective bulk modulus of the material [10-11].

The effective density \( \rho \) and the bulk modulus \( K \) can be written as,
The expression for $G$ and $G'$ is defined as the following.

$$G(\omega) = \frac{1}{\sigma \Lambda_0} \left[ \sigma^2 \Lambda^2 \Theta^2 + 4 j \omega a_\infty^2 \rho_0 \eta \right]^{1/2}$$ \hspace{1cm} (2.34)

$$G'(\omega) = \left[ 1 + \frac{j \omega a_0 B^2 \Lambda^2}{16 \eta} \right]^{1/2}$$ \hspace{1cm} (2.35)

in which $B$, and $\eta$, are the Prandtl number and the viscosity of the air in m/s, respectively.

The viscous and thermal characteristic lengths can also be calculated using the following equations.

$$\Lambda = \left[ \frac{8a_\infty \eta}{c^2 \sigma \Theta} \right]^{1/2}$$ \hspace{1cm} (2.36)

$$\Lambda' = \left[ \frac{8a_\infty \eta}{c' \sigma \Theta} \right]^{1/2}$$ \hspace{1cm} (2.37)

in which $c'$ is a numerical coefficient related to the geometry of the pore section.
2.8. References


Chapter 3: Design of Open Porous Acoustic Foams

3.1. Introduction

Before developing any acoustic foam, it is necessary to investigate the important parameters affecting the acoustic properties. Hence, a study on the effect of pore size, porosity, and thickness was conducted in this work. The salt particle leaching method is known as one of the most feasible strategies to produce open porous material while having close control on the cell size, cell density, and thickness. This method has been used by many researchers and was used in this chapter.
3.2. Experimental

3.2.1. Materials

Polypropylene (PP) grade number FP800-00 powder supplied by Equistar was used in this study. This material has a melt flow index of 35 g/10 min (ASTM-D1238) and a density of 0.909 g/cc. This material was supplied in spherical powder size of 5-50 µm. This material has a high index value and is an appropriate material for an injection molding process. Further, polymer with a high flow index is less viscous and is easier to flow and sinter together in the salt leaching method. The fine powder size of PP powder selected in this experiment allows for better material mixing and sintering. Commercially available sodium chloride salt was used in this experiment. The salt was sieved into 3 different ranges of particle sizes: 106-250 µm, 250-500 µm, and 500-850 µm before it was used.

3.2.2. Strategy to Synthesize Open Porous Foams

Foams are initially closed-cell and an additional effort is usually needed to change it to open-cell them. Many strategies have been developed for cell opening including: plasticizing of the cell wall with secondary blow agents [1], maintaining a high temperature difference between the surface and core of the foam extrudate [2], thinning of the cell wall by a high expansion ratio [3], mechanically rupturing the cell walls, and producing non-homogeneity on the cell walls [4]. The particulate (salt) leaching method [5] is a feasible method and enables close control of the cell morphology and the thickness of the foams. In order to extract the contribution of the cell size, the porosity, and the thickness of the acoustic foams, the particulate leaching method was selected to produce foam samples. In this study, foam materials with different cell size, porosity
and thickness were developed using the salt leaching method and the effect of each parameter on the absorption coefficient of the foams was studied.

3.2.3. Processes of Making Open-Cell Foams

The compression molding technique along with the particulate leaching method was used to fabricate open porous materials. The following are the four main stages of this experiment. In the first stage, salt was sieved into 3 particle size ranges: 106-250µm, 250-500 µm, and 500-850 µm for the experiment. In the second stage, six different material compositions of the salt and polymer were created as shown in Table 3.1. The three different range salts were dry blended with polymer under three different salt/polymer weight ratios of 70%, 80%, and 90%.

Table 3.1: Prepared compositions of polymer/salt to produce acoustic foams.

<table>
<thead>
<tr>
<th>Salt size range</th>
<th>106-250µm</th>
<th>Salt size range</th>
<th>250-500µm</th>
<th>Salt size range</th>
<th>500-850µm</th>
<th>Weight ratio salt/polymer</th>
<th>Weight ratio salt/polymer</th>
<th>Weight ratio salt/polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>composition #1</td>
<td>✅</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>70%</td>
<td>80%</td>
<td>90%</td>
</tr>
<tr>
<td>composition #2</td>
<td>✅</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80%</td>
<td></td>
</tr>
</tbody>
</table>
In the third stage, a compression-molding machine, which was heated up to 170°C, was used to shape materials of different compositions using a mold. The mold had a 30mm hole which was prepared for shaping of the materials in order to carry out the acoustic test. Materials were introduced to the mold and were heated for 10 min in the mold and then they were compressed under 1 Ton, 2 Tons, then 3 Tons, each for 5 minutes. Finally, the materials were collected from the mold and their weights were measured. In the fourth stage, all of the prepared materials were immersed in hot water (about 50 °C) for three days. Finally, samples were dried by keeping them in a regular oven at 40 °C for 10 hours. A silver nitrate (AgNO3) solution was used to make sure that the salt was completely leached out. A white residue would be generated with the presence of Ag+ and cl- ions in the solution. When the white residue was observed by adding Silver nitrate, the samples were kept in the hot water for a longer time, to make sure that all of the salt had been removed from the samples. Five samples from each composition were prepared and they were characterized.

3.3. Characterization
Two sets of the samples, one with the same pore sizes and the another with the same porosity, were developed and all of the samples in both sets were characterized for porosity, static flow resistivity, tortuosity, viscous length, and thermal length. Of the five macroscopic properties identified in the Johnson-Allard formulation that models the propagation of sound in a porous material, the porosity and air flow resistivity of the samples were measured directly. The other three properties were obtained using the acoustical characterization technique proposed by Atalla and Panneton [6]. Table 3.2 summarizes the obtained values for the porosity, static flow resistivity, tortuosity, viscous length, and thermal length for the developed samples.

Table 3.2: Characterization results for developed acoustic foams.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Ratio:</td>
<td>9:1</td>
<td>9:1</td>
<td>9:1</td>
<td>7:1</td>
<td>5:1</td>
</tr>
<tr>
<td>Salt Particle Size</td>
<td>500-850µm</td>
<td>250-500µm</td>
<td>106-250µm</td>
<td>106-250µm</td>
<td>106-250µm</td>
</tr>
<tr>
<td>Porosity</td>
<td>81.2% ±1.2</td>
<td>80.63% ±1.5</td>
<td>79.96% ±2.5</td>
<td>75.25% ±1.9</td>
<td>60.82% ±3.4</td>
</tr>
<tr>
<td>Static Flow Resistivity (Pa.s/m²)</td>
<td>1.05E5 ±2207</td>
<td>1.17E5 ±2050</td>
<td>1.21E5 ±2352</td>
<td>1.30E5 ±3319</td>
<td>3.9E5 ±4072</td>
</tr>
<tr>
<td>Tortuosity</td>
<td>1.14</td>
<td>1.32</td>
<td>1.43</td>
<td>2.62</td>
<td>2.95</td>
</tr>
<tr>
<td>------------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>±0.72</td>
<td>±0.65</td>
<td>±0.81</td>
<td>±1.2</td>
<td>±1.8</td>
</tr>
<tr>
<td>Viscous Length (mm)</td>
<td>16.15</td>
<td>15.29</td>
<td>12.46</td>
<td>8.82</td>
<td>5.15</td>
</tr>
<tr>
<td></td>
<td>±5.6</td>
<td>±3.5</td>
<td>±4.3</td>
<td>±5.3</td>
<td>±3.2</td>
</tr>
<tr>
<td>Thermal Length (mm)</td>
<td>52.5</td>
<td>45.9</td>
<td>25.2</td>
<td>11.26</td>
<td>7.59</td>
</tr>
<tr>
<td></td>
<td>±8.5</td>
<td>±5.6</td>
<td>±4.7</td>
<td>±3.6</td>
<td>±2.4</td>
</tr>
</tbody>
</table>

3.4. Effect of Pore Size on the Absorption Coefficient of the Open-Cell Foams

Figure 3.1 shows the calculated absorption coefficient for the developed samples in three different pore size ranges. No significant variation was obtained for the absorption coefficient in the tested pore sizes. A mountain shape for the absorption coefficient was observed for all of the samples within a frequency of 800-6300Hz. The absorption coefficient increased as the sound frequency increased from 800Hz to 4500Hz for all of the samples examined. In this frequency range, the slope of the change of the absorption coefficient was the highest for the foam with a cell size in the range of 500-850 µm and was the lowest for the sample with the cell size in the range of 106-250 µm.

The absorption coefficient changed differently for the samples when the frequency was increased from 4500Hz to 6300 Hz. For the samples with pore sizes in the range of 106-250µm,
250-500 µm, and 500-850 µm, peak absorption of 0.98, 0.92, and 0.91 were observed at frequencies of 5850, 5500, and 5200 Hz respectively.

![Figure 3.1: Absorption coefficient of the samples with different pore sizes.](image)

### 3.5. Effect of Porosity on the Absorption Coefficient of the Open-Cell Foams

Figure 3.2 shows the calculated absorption coefficient for the developed samples in three different porosities having a pore size in the range of 106-250 µm. For frequencies up to around 3500 Hz, no significant variation was obtained for the absorption coefficient when the porosity was varied from 75.25% to 79.96%. However, a significantly lower absorption coefficient was observed for the sample with a porosity of 60.82% at a frequency of >3500 Hz. For the samples with 79.96%, 75.25%, and 60.82% porosity, peaks of 0.98, 0.96, and 0.71 at frequencies of 5800, 5800, and 6300 Hz were observed, respectively. For the frequency range of 800 to 3400 Hz, a sample with 60.82% showed a slightly higher absorption coefficient among the samples.
Figure 3.2: Absorption coefficient of the samples with different porosity.

3.6. Effect of Air-Gap on the Absorption Coefficient of the Open-Cell Foams

3.6.1. Samples with Different Porosities

Figure 3.3 shows the absorption coefficient of the samples with different pore sizes (106-250 µm, 250-500 µm, and 500-850 µm) when they are backed with a 4mm, 8mm, and 12mm air cavity. The absorption coefficient curves for all samples exhibited a mountain shape when they are backed with a cavity. The peak of the mountain-shaped curves moved towards a low frequency when the thickness of the air cavity had been increased.
(a)

(b)
Figure 3.3: Absorption coefficient when they are backed with a 4mm, 8mm, and 12mm cavity length for the samples with a pore size of (a) 106-250µm, (b) 250-500 µm, and (c) 500-850 µm.

3.6.1. Samples with Different Cell Size

Figure 3.4 shows the absorption coefficient of the samples with different porosities (60.82%, 75.25%, and 79.96%) when they are backed with a 4mm, 8mm, and 12mm cavity. In all of the samples, the obtained mountain shape curves for the absorption coefficient did not vary much when they were backed with a cavity. The peak frequency moved towards a low frequency by increasing the air-cavity thickness.
Figure 3.4: Absorption coefficient when they are backed with a 4mm, 8mm, and 12mm cavity length for the samples with a porosity of (a) 60.82\%, (b) 75.25\%, and (c) 79.96\%. 
3.7. References


Chapter 4: Development of New Technology to Produce Open Porous Acoustic Foams Using Injection Molding for Sound Insulation

4.1. Introduction

Open-cell foam materials have many applications such as sound and thermal insulators [1-4], filter and separation membranes [5,6], scaffolds [7-9], battery electrode supports [10, 11], and as in printing [11]. Polymeric open-cell foams can be developed for such applications. However, commercial open-cell polymeric foams have been almost exclusively manufactured with polyurethane thermoset materials [12-19], and the manufacturing technologies for open-cell
thermoplastic foams have not been extensively developed [20]. Some effort has been focused to create open-cell thermoplastic foams using different methods [11, 21-26]. These methods include soluble particulate leaching from a polymer matrix [9, 27-29], inter-polymer blending [21], polymer resin grafting [22], soft blowing agent blending [11], mechanical punching of foams with fine needles [23], stretching mineral-filled polymers [24], changing core and skin temperatures of polymer/gas mixtures [25], and reduction of the cell wall thickness [26]. However, most of these approaches have been tried on a batch scale.

A few people have tried to use processing technologies such as extrusion [1, 30, 31] and rotational molding [28] to create open-cell thermoplastic foams. Lee et al. used a non-homogenous melt structure of low-density polyethylene (LDPE) to create open-cell foams in extrusion [30]. Further, they used two different semicrystalline polymer blends (i.e. polypropylene (PP)/metallocene polyethylene (mPE) and linear PP/low-density PE (LDPE) with different crystallization temperatures to produce open-cell foams [1, 30]. Chu et al. combined rotational foam molding and particulate leaching to produce foams with open-cell networks for acoustics. They successfully fabricated foams with about 85% of open-cell content [28].

Injection molding is one of the most cost-effective and widely used thermoplastic processing technologies. It has also been frequently used in the production of high-density foams [32-35]. Since foaming takes place in an enclosed mold cavity, the range of achievable void fractions and cell densities is limited in the regular foam injection-molding process [36-38]. Therefore, it is challenging to produce an open-cell structure using the regular foam injection-molding process, and new strategies need to be developed to achieve highly expanded foams with an open-cell structure. To create an open-cell structure in injection-molded samples, introducing a high void
fraction and shearing the expanded cells in polypropylene foams [38] have been tried. Recently, Kramschuster et al. [9] and Chi et al. [39] produced highly porous and interconnected material for tissue engineering scaffolds by using material combinations, supercritical fluid processing, and particulate leaching techniques in injection molding. Very recently, Wu et al. also produced open porous thermoplastic polyurethane scaffolds using supercritical CO$_2$ in the regular foam injection-molding process [40]. They used a relatively high volume of supercritical CO$_2$, i.e., 6 wt.% and achieved injection-molded foams with a maximum open-cell content of 71%.

To achieve significantly higher void fractions, along with a uniform cell morphology and a good surface quality, the foam injection-molding process can be practiced using the mold opening and GCP techniques [38, 41-48]. In this process, the mold cavity is first pressurized, and then the polymer/gas mixture is injected to fully fill the pressurized cavity. Subsequently, while the gas is being depressurized in the cavity, the mold is opened in the thickness direction to achieve the desired final thickness and the resultant high void fraction. The pressure drop due to cavity depressurization and mold opening causes cell nucleation, and growth occur uniformly in the entire injection-molded sample [38, 41-48]. However, this technology has been mostly used to produce a closed-cell structure. In our previous work, we demonstrated how this technology can be used to create cavity-integrated polypropylene (PP) foams with enhanced acoustic properties [38]. But cavity-integrated foams have poor mechanical properties due to the existence of gap in the core of the sample. To broaden their applications, such foams’ acoustic properties should be enhanced while maintaining their high mechanical properties by eliminating this problem.

Our current work combines the regular foam injection-molding process with mold opening and GCP to achieve highly-expanded pure PC foams with an open-cell structure. We propose
that the closed-cell foam structure can be effectively converted to an open-cell structure. This could be achieved by introducing a sufficient degree of one-dimensional expansion and by regulating the mold opening during cell growth. To investigate the feasibility of the proposed technique, several degrees of one-dimensional expansion (that is, mold opening), along with varying injection flow rates and melt temperatures, were investigated. The microstructure, the degree of open-cell content, the sound and thermal insulation behaviors, and the mechanical properties of the foams were characterized.

4.2. Experimental

4.2.1 Materials Selection

Because of its high industrial value and its wide range of applications at specifically high-temperature service conditions, PC was used in this study. The commercially available injection molding grade of PC, Lexan Resin HF1110 from Sabic was used. It was provided in a pellet form and has a specific gravity of 1.2 g.cm\(^{-3}\), a melt flow index of 25 dg/min. (190°C/2.16 kg), and a glass transition temperature of 147 °C. The pellets were dried at 120 °C for 4 hours before injection molding, as recommended by the manufacturer. Nitrogen (N\(_2\)) was supplied by Linde Gas, Canada and was injected into the barrel in the supercritical fluid state as the physical blowing agent. It was also used for the GCP.

4.2.2. Sample Preparation

A 50-ton Arburg Allrounder 270/320 C injection molding machine (Lossburg, Germany) with a 30-mm diameter screw and equipped with MuCell\textsuperscript{®} Technology (Trexel, Inc., Woburn, Massachusetts) and GCP [30-32] module (Caropreso Associates, MA, US) was used to conduct
the experiments. A GCP module in injection molding inserts high pressure gas to the cavity of the mold right before melt injection, holds the pressure in the cavity, and finally releases the gas from the cavity right after melt injection. The mold contained a rectangular cavity (135 mm × 111 mm × 3.2 mm) with a fan gate at one end. More details about the mold can be found in [38]. The mold cavity was first pressurized at about 6 MPa. Then, the polymer/gas mixture was injected into it while the GCP was maintained. The mold cavity was completely filled by a full shot, and the foam expansion was achieved by opening the mold [34, 36-37]. The mold cavity pressures were measured at three different locations, i.e., near the gate, in the middle of the cavity, and near the end of the cavity during the entire injection cycle, using three PT462E Dynisco pressure transducers and a DAQ board (Compact DAQ Kit, National Instruments).

Table 4.1 summarizes the fixed and varied foam injection-molding parameters. The optimum values for the fixed parameters were determined by a series of trial and error experiments. The degree of mold opening, the melt temperature, and the injection flow rate were determined as the most influential parameters on the final structure of the expanded samples. Thus, they were varied to investigate their effects on the foam structure and the open-cell content. In all of the experiments, the other parameters remained unchanged. It should be noted that foams samples with three flow rates: 100, 50, and 25 cm³/s were examined. However foams produced with flow rate of 50 and 25 cm³/s had significant non-uniformity due to slow filling of the cavity and temperature gradient on the polymer melt. Hence only foams produced in 100 cm³/s were studied.

Table 4.1: Fixed and varied parameters in the foam injection molding of PC.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot size (cm$^3$)</td>
<td>Full, 52</td>
</tr>
<tr>
<td>Barrel pressure (MPa)</td>
<td>19</td>
</tr>
<tr>
<td>Gas injection pressure (MPa)</td>
<td>24</td>
</tr>
<tr>
<td>Screw speed (rpm)</td>
<td>200</td>
</tr>
<tr>
<td>Metering time (s)</td>
<td>10</td>
</tr>
<tr>
<td>Gas counter-pressure (MPa)</td>
<td>6 MPa</td>
</tr>
<tr>
<td>Delay in mold opening (s)</td>
<td>2</td>
</tr>
<tr>
<td>Mold temperature (ºC)</td>
<td>35</td>
</tr>
<tr>
<td>N$_2$ content (wt. %)</td>
<td>0.3</td>
</tr>
<tr>
<td>Injection flow rate (cm$^3$/s), variable</td>
<td>100</td>
</tr>
<tr>
<td>Degree of mold opening (mm), variable</td>
<td>0,2,6,5,7,9,1,12.8</td>
</tr>
<tr>
<td>Melt temperature (ºC), variable</td>
<td>280, 300, 320</td>
</tr>
</tbody>
</table>

### 4.3. Characterization
4.3.1. Foam Structure Characterization

The foam density was measured either geometrically or by using the water-displacement method (ASTM: D792-08). The expansion ratio ($\phi$) was calculated using Equation 1.

$$\phi = \frac{d_s}{d_f}$$

(4.1)

where $d_s$ and $d_f$ are the density of the unfoamed solid material and foamed sample, respectively.

To study their microstructure, the samples were freeze-fractured and then coated with platinum using a sputter coater. The microstructures were then examined using scanning electron microscopy (SEM), JEOL JSM-6060. The thickness of the coating was 200-300nm, and the acceleration voltage was 20 volts. The cell density was calculated using Equation 2.

$$Cell\_Density = \left( \frac{n}{A} \right)^{\frac{3}{2}} \phi$$

(4.2)

where $n$ is the number of cells in the micrograph; $A$ is the area of the micrograph. The open cell content (O.C.) of the foams was calculated using Equation 3.

$$O.C. = (1 - \frac{V_a}{V_g}) \times 100\%$$

(4.3)

where $V_a$ and $V_g$ are the actual volume and the geometric volume of the foam, respectively.
4.3.2. Acoustic Property Characterization

The injection-molded samples were evaluated for their acoustic behavior, that is, the sound wave transmission loss, which represents the energy that the sound wave loses when it passes through the acoustic fence (see Figure 4.1). Based on the concept of acoustic attenuation, this refers to the decibels of sound wave power that are lost when the wave passes through the sample. The transmission loss (TL) for an acoustic wall can be calculated using Equation 4.

\[ TL = 10 \log \frac{I_2}{I_1} \]  

(4.4)

where \( I_1 \) and \( I_2 \) are the sound intensity before sound waves hits the acoustic wall and the intensity of the sound wave right after it passes through the wall.

TL can vary from 0 to any value. Samples were cut into 100 mm of diameter, and their transmission loss was measured using an impedance tube and the Tube-X\textsuperscript{TM} utilities package in accordance with the ASTM: E1050-12 standard. The package was able to account for the effects of the temperature, the barometric pressure, and the attenuation of the measured quantities [15].
4.3.3. Thermal Insulation Characterization

A transient plane source (TPS) hot disk thermal constants analyzer (Therm Test Inc., TPS 2500, Sweden) was used to measure the thermal conductivity ($\lambda$) of the solid and foamed samples, as explained in [37]. Figure 4.2 shows the encapsulated nickel-spiral sensor sandwiched between two halves of the sample (30 mm $\times$ 30 mm each), assuring that the halves are in contact with the sensor. Two halves of the test samples were cut from the injection-molded sample. During testing, a constant electric power was supplied to the sensor, and the temperature increase was recorded. For each test, the power output and test duration ranged between 0.005-0.025 W and 15-80 s, respectively, depending on each sample’s thermal characteristics. The tests were all conducted at the room temperature. In each one, three samples
were tested with at least three measurement replications, and the grand average values were reported.

![Figure 4.2: Schematic of the transient plane source set up for thermal conductivity measurement.](image)

4.3.4. Mechanical Property Characterization

The ASTM D790 standard was adopted for the flexural three-point bending test of solid and foam samples. The specimens were cut from the injection-molded parts. All of the specimens had a width ($w$) of 12.7 mm and a span length ($L$) of 80 mm. Depending on the specimen’s thickness, the crosshead speed varied between 0.5-1.5 mm/min., assuring that the strain rate at its outer surface did not deviate from 0.01 mm/mm/min. [39]. A computer-controlled Instron mechanical testing system was used to carry out the bending tests, and five specimens were tested for each case.
4.4. Results and Discussion

4.4.1. Foam Structure

Figure 4.3a schematically illustrates the foam injection-molded sample structure and Figure 4.3b shows representative SEM micrographs from various locations of the samples. Three distinct regions were observed in the morphology: the skin layer, the transition region, and the core region. As expected, the skin layer presented a solid (unfoamed) structure that was about 0.5-0.7 mm thick. Both the transition and core regions had a cellular structure, but with different cell morphologies. As Figure 4.3b shows, the transition region formed a closed-cell region (0.2-0.4 mm) immediately next to the skin layer, and followed by another region (0.8-1.1mm) that had severely elongated cells in the thickness direction.
Figure 4.3: (a) A schematic showing the overall structure of the foam injection-molded sample using mold opening, and (b) Representative SEM micrographs, obtained at temperature of 300°C, showing the skin layer and the transition and core regions of the injection-molded samples using mold opening.

In the core region, which was the major part of the injection-molded samples, the cells were relatively uniform in size and in distribution, and they were interconnected with an open-cell structure in most cases. The differences between the cell morphology in the core and transition regions originated from the temperature differences. The sample started to solidify from the skin layer. Consequently, the growth of the cells in the transition region was hindered sooner, and this resulted in the formation of smaller-sized cells with a closed structure. Some of these closed cells adjacent to the core region were elongated in the thickness direction due to the stretching caused by the mold opening in that direction. The following is the explanation for the formation of the open-cell structures in the core region.

The opening of the mold could enable excessive cell growth, and extremely thin cell walls [32, 35]. Because of the limitation of the equipment used in this study, unfortunately it was not
practical to have a close control on the opening speed. Pinholes on the cell walls could be created as a result of the induced biaxial stretching from expansion and polymer shrinkage of the thin walls during the solidification [40-43]. Furthermore, opening of the mold caused the melt to flow one-dimensionally, causing the cells to grow further in the thickness direction and to experience additional shear and extensional stresses. Especially, the low melt strength of linear polycarbonate used in our study can cause cell wall rupturing and opening easily.

Figure 4.4a shows the variations of the set ratio and the actual expansion ratio, as a function of the degree of mold opening. The mold-opening length of 0, 2.5, 5, 9, and 10.6 mm in this figure represents samples with 3.2, 5.7, 8.3, 12.2, and 13.8 mm in thickness, respectively. Due to the existence of the solid skin layer and the transition region, the actual expansion ratio in the core region was different from the set expansion ratio. The actual expansion ratio was higher than the set ratio. Both increased proportionally with increased mold-opening length. To evaluate its uniformity across the thickness of the core, the actual expansion ratio was measured at two different locations in the core region, namely in Core I and Core II (Figure 4.3a). In each case, the expansion ratios measured at the Core I and II locations were very similar. This indicated that a uniform degree of expansion ratio could be achieved across the entire thickness of the core region. It was observed that opening of the mold up to 10.6 mm caused further expansion. At the set processing parameters, when the degree of mold opening was increased, more space was provided for the growing cells in the sample’s thickness direction. Thus, the cells could grow further because of the decreased pressure and the increased space. But we noted that further opening of the mold more than 10.6 mm did not result in any additional expansion.
Figure 4.4: (a) Variations of the set and actual expansion ratios with the degree of mold opening (gas content: 0.3 wt.%, melt temperature: 300 °C), and (b) Variation of the open-cell content with actual expansion ratio.

Figure 4.4b shows the open-cell content variations with the actual expansion ratio in the Core I and II regions. The open-cell content increased with the expansion ratio at two different rates. As the expansion ratio was increased from 1 to 4, the open-cell content did not increase much. Further increase of the expansion ratio, however, significantly increased the open-cell content. It seems that the cell walls were relatively thick at the very low expansion ratios and, as the expansion ratio was increased, the cell wall thickness started to decrease due to cell growth [44]. It may be assumed that there was a critical expansion ratio at which cell wall thinning could have occurred sufficiently to facilitate the pin hole development in most of the cell walls. As Figure 4.4b shows, at least a four-fold expansion was required to effectively interconnect the cells. At an expansion ratio of 7.2, a structure with open-cell content close to 79% could be successfully produced. Further, for both Core I and II regions, the open-cell content was similar, indicating a uniform degree of cell opening across the entire core region. To study more on cell opening and possible cell coalescence during cell growth, the cell density was calculated. The samples with expansion ratios of 4.2, 6.0, and 7.2 exhibited the cell density of 8.2E6/cm³, 2.2E6/cm³, and 1.5E6 cells/cm³, respectively. This indicates that cell coalescence took place actively during cell growth especially between expansion ratios of 4.2 and 6.0. The SEM micrographs of injection-molded samples with actual expansion ratios of 4.2, 6, and 7.2 are shown in Figure 4.5. An average cell size of 58 µm, 107 µm, and 132 µm was respectively observed.
To optimize the processing condition and develop highly expanded open-cell foams, the effect of the melt temperature was studied. Figure 4.6 shows the obtained expansion ratio and the open-cell content in three melt temperatures 280°C, 300°C, and 320°C. The melt temperature played an important role in achieving the maximum expansion ratio. The maximum achievable expansion ratio decreased quite significantly with a decreased melt temperature. When the melt temperature was decreased from 320°C to 280°C, the maximum expansion ratio dropped from 8.5 to 6.0, respectively. The decreased melt temperature increased the viscosity and stiffness of the melt, and caused rapid solidification. Further, in the case of a lower melt temperature, the solidification temperature was reached earlier, resulting in a reduced time for cell growth, and consequently, the cells could not grow to their full potential with the given set void fraction.
Figure 4.6: (a) Variations of the maximum achievable expansion ratio as a function of melt temperature, and (b) variation of the open-cell content with melt temperature.

The open cell content of the foams was characterized as well. At 280 °C, the average open-cell content was only about 55%. As the melt temperature increased to 300 °C, the average open-cell content increased to 80%. But a further increase in the melt temperature to 320°C did not enhance the open-cell content. Overall, a relatively acceptable uniformity of open-cell content was achieved in the injection-molded samples. However, the open-cell content in the Core I region was slightly higher than that in the Core II region, most likely from the higher temperature of the Core I region during cell growth. This is also reflected by the slightly higher expansion ratio in the Core I region (Figure 4.6a), and the higher temperature further created slightly thinner cell walls that were more prone to pin-holing during the solidification and shrinkage.

4.4.2. Sound Insulation Properties

To characterize the sound insulation behaviors, samples of Table 4.2 were manufactured using a melt temperature of 320 °C and an injection flow rate of 100 cm³/s. The other processing conditions were identical to those in Table 4.1. Figure 4.7 shows the sound wave transmission loss variations in the injection-molded foams at a broad frequency spectrum. Two regions can be distinguished in the frequency spectrum of the transmission loss. In the frequency range of 1600 to 4600 Hz, the transmission loss significantly increased with a decrease in the relative density. For example, at 1600 Hz a transmission loss of about 20 dB in the solid samples increased to
more than 55 dB when the relative density was decreased to 0.2. At higher frequencies, however, the transmission loss in all of the samples converged to a lower value, independent of their relative density. In panel-type sound absorbers, the resistance of the front panel for fast shaping attenuates the energy of the sound wave [45]. This attenuation depends strongly on the mass of the panel. It has been shown that each time the panel mass is doubled, its transmission loss is improved by 6 dB. Therefore, the small expansion of the foam in the transition region close to the skin layer (Figure 4.3) is an advantage as it maintains a relatively dense front layer [45]. On the other hand, an open-cell structure in the core region would improve the sound wave absorption [15, 45].

Table 4.2: Degree of mold opening and the resultant set expansion ratio and relative density of the injection-molded samples.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Open-cell content</th>
<th>Degree of mold opening (mm)</th>
<th>Set expansion ratio (-)</th>
<th>Relative density (-)</th>
<th>Average cell size (µm)</th>
<th>Average cell density (Cells/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.0</td>
<td>1.0</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2.6</td>
<td>1.8</td>
<td>0.55</td>
<td>42</td>
<td>1.3E7</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>5.7</td>
<td>2.8</td>
<td>0.36</td>
<td>63</td>
<td>9.3E6</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>4</td>
<td>77</td>
<td>9.1</td>
<td>3.8</td>
<td>0.26</td>
<td>115</td>
<td>2.7E6</td>
</tr>
<tr>
<td>5</td>
<td>82.5</td>
<td>12.8</td>
<td>5.0</td>
<td>0.20</td>
<td>163</td>
<td>8.2E5</td>
</tr>
</tbody>
</table>

(a)
Figure 4.7: (a) Transmission loss versus frequency for the foam injection-molded samples with various relative densities, and (b) area under transmission loss vs. frequency curves for foam injection-molded samples with various relative densities.

Further, the transmission loss spectrum of all the samples presented a minimum value, which corresponded to the transmission loss at their natural frequency [45]. It was seen that the natural frequency of the samples increased with a decreased density. In other words, the minimum transmission loss occurred at higher frequencies as the expansion ratio increased. This, in turn, widened the frequency range at which the transmission loss was higher, implying that such highly expanded samples can be used in a variety of environments with various noise frequencies. In addition, the minimum transmission loss corresponding to the natural frequency slightly increased as the expansion ratio increased.

To assess the overall performance of the samples in a wide frequency range, the area under
the transmission loss vs. the frequency curve was calculated and is shown in Figure 4.7b as a function of the relative density. Clearly, the area increased with a decreased relative density. The improvement of the transmission loss by the introduction of foaming (for the same mass) was achieved by three different mechanisms: 1) the increased thickness of the foam between the two skin layers [46]; 2) the increase in the structural damping, which was higher in the more expanded foam due to the skin layer’s resonant bending mode acting as a front panel [47]; and 3) an increased open-cell content obtained at a lower density [23, 48] that damped the energy of air molecules traveling from one cell to another via thermal conductivity and viscosity [49].

4.4.3. Thermal Insulation Properties

Figure 4.8 shows the variations of the thermal conductivity of injection-molded foam samples with relative density. Overall, as expected, the thermal conductivity decreased with decreased relative density. By introducing a relative density of 0.2, the thermal conductivity of the PC solid samples reduced from 0.20 W/m.K to about 0.04 W/m.K, i.e., more than fivefold. At higher relative densities (that is, at lower expansion ratios), the thermal conductivity increased at a greater rate with an increased relative density. However, at a relative density lower than 0.36, the rate of change of the conductivity was not high. The theoretical thermal conductivity of the high-density foams can be predicted using the following equation [50]:

$$\lambda_{\text{theo}} = \lambda_{\text{gas}} V_{\text{gas}} + \xi \lambda_{\text{matrix}} V_{\text{matrix}}$$  \hspace{1cm} (4.5)

where $\lambda_{\text{gas}}$ and $\lambda_{\text{matrix}}$ are the conductivity of nitrogen gas or air (0.026 W/m.K) [49] and conductivity of the PC matrix, respectively. $\xi$ is the tortuosity factor, a parameter directly related to the inherent irregularity of foam, which implicitly considers the effect of cellular structure.
(e.g., cell size, cell density, cell wall thickness, etc.). By fitting the experimental data to Equation (4.5) in the high and low relative density ranges (Figure 4.8), different tortuosity factors were obtained. This difference in thermal conductivity behavior can thus be attributed to the foams’ microstructure having different relative densities. At higher relative densities, the majority of the cells had a closed structure and a smaller size, with a relatively spherical shape. This decreased the contribution of the gaseous phase (the first term in Equation 5), and increased the conductivity of the matrix. On the contrary, at lower relative densities, with a higher degree of mold opening, the void fraction was increased and the polymer matrix contribution was decreased. It has been known that the thermal conductivity decreases with a decrease in the cell size [51]. So the higher elongational viscosity (with strain hardening) and higher elasticity, which affect the cell nucleation rates through the local stress variations [52-54] and cell coalescence though the melt strength, will influence the thermal conductivity of the final products.

![Graph showing thermal conductivity vs. relative density]

- Linear (Low relative density) \( y = 0.08x + 0.02 \) (\( R^2 = 0.96 \))
- Linear (High relative density) \( y = 0.23x - 0.03 \) (\( R^2 = 0.99 \))
Figure 4.8: Variations of thermal conductivity of foam injection-molded samples with relative density. The lines are the least-square fits to the experimental data at high and low relative density ranges.

4.4.4. Flexural Properties

Figure 4.9 shows the specific flexural modulus and the strength of the injection-molded solid and foamed samples with various relative densities. Specific values of the modulus and the strength were obtained by dividing the actual values by the density of the tested samples. The variations of the flexural properties with relative density were not monotonic. At higher relative densities, the introduction of foaming did not significantly decrease the specific flexural modulus and strength. For example, at a relative density of 0.36, these values decreased by only 14% and 5%, respectively, compared with their corresponding solid values. With a further decrease in the relative density, the specific modulus and strength of the foams sharply decreased. At the lowest relative density, their values came to 18% and 55%, respectively, of their corresponding solid values. The sharp decrease in flexural properties at lower relative densities must have been related to the creation of the open-cell structure with thin cell walls. This was in contrast to the relatively smaller-sized closed cells in the foams with high relative densities.
4.5. Conclusion

Highly expanded rigid polycarbonate (PC) foams with a uniformly distributed open-cell structure were developed using injection-molding process equipped with a mold opening technique and gas counter-pressure (GCP). The cellular structure, sound and thermal insulation, and mechanical performance of the foams were also evaluated.

PC foams with expansion ratios of as high as eightfold and open-cell contents of as high as 85% were successfully fabricated by tuning the foam injection-molding processing parameters. It was found that the degree of mold opening, the melt temperature, and the injection flow rate were the most influential parameters in creating a cellular structure with a high open-cell content.

The introduction of high expansion with a high open-cell content to the solid PC samples increased the sound wave transmission loss up to 2.5 times and decreased the thermal conductivity by more than fivefold, while maintaining more than 50% of the specific flexural strength. This research discloses that highly-expanded rigid open-cell PC foams can be effectively used in the sound and thermal insulation applications.
4.6. References


Chapter 5: Development of Air-Gap Integrated Acoustic Open-Cell Foams for Sound Absorption

5.1. Introduction

In chapter 3, simulation results proved that with considering an air-gap, the peak absorption coefficient of open-cell foams may decrease significantly. It was absorbed that for low-frequency sound insulation with conventional open-cell foams, a considerable foam thickness is required [1]. Multi-layer acoustic foams [2-3] constructed with a front panel, open-cell foam, and an air-gap promise to provide alternative solutions for low-frequency sound absorption (400Hz to
1600Hz). In some applications, the front panels were perforated to enhance their acoustic behavior [4-5]. The costs associated with multi-layer acoustic foams are relatively high and, in most cases, the open-cell foams used in such insulators are not recyclable. It is thus of great value to develop cost-effective and recyclable alternatives to these resonators. In this study, the conventional foam injection-molding process equipped with mold opening and gas counter-pressure techniques was used to produce multilayer sound insulation foams. It successfully produced relatively low-density open-cell foams and created air-gap integrated acoustic foams. A mechanized perforating apparatus was also developed to assess the effects of perforation on the structure’s acoustic behavior. The sample structure, cell morphology, and acoustic behavior of the foams were then thoroughly investigated.

5.2. Experimental

5.2.1. Sample Preparation – Foam Injection Molding

To achieve an effective acoustic foam using the injection-molding process, the three requirements should be met: (i) capability to produce foams with relatively high void fractions; (ii) to interconnect the cells to increase the open-cell content; and (iii) to create cavity inside the foams to enhance their acoustic behavior. The opening of the mold enabled the melt to flow one-dimensionally in the sample thickness direction, causing the cells to grow further in that direction and to experience additional shear and extensional stresses. The temperature of the polymer melt was tuned to obtain optimum melt strength and thus enhanced the cell growth capacity while preventing the cells from collapsing [6-7]. Excessive cell growth resulted in extremely thin cell walls and thus pinholes on the cell walls could be created as a result of the induced biaxial stretching from expansion and polymer shrinkage of the thin walls during the
solidification [7-8]. Especially, the low melt strength of linear polypropylene used in our study can cause cell wall rupturing and opening easily [9]. After the cells were expanded and solidified, a further opening of the mold in a timely manner initiated a crack in the foam core as a result of residual stress on the foam. Eventually, an opening in the mold caused a full-length crack in the foam core and a cavity was developed in the middle of the foam. The mold was kept cold (i.e., at room temperature) to enable rapid solidification of the foam and to create a residual stress in the foam core. The length of the mold opening was adjusted to produce a foamed structure without a cavity and also cavity-integrated acoustic foams of different thicknesses.

The commercially available injection-molding grade of polypropylene (PP), Certene PHM35 was used. It was provided in a pellet form and had a specific gravity of 0.903 g/cm³, a melt flow index of 35 g/min, and a Vicat softening temperature of 152 °C. Nitrogen (N₂) was supplied by Linde Gas, and used as the physical blowing agent. A 50-ton Arburg Allrounder 270/320 C injection-molding machine (Lossburg, Germany), with a 30-mm diameter screw equipped with MuCell® technology (Trexel, Inc., Woburn, Massachusetts), and a gas counter-pressure module (Caropreso Associates, MA, US) were used to conduct the injection-molding experiments. The mold contained a rectangular cavity with a fan gate at one end. The cavity dimensions were 135 mm × 111 mm × 3.2 mm. More details about the mold can be found in [10-11]. The mold cavity was first pressurized at about 6 MPa, and then the polymer/gas mixture was injected into it while the gas counter-pressure was maintained to avoid premature cell nucleation and growth during filling. The mold cavity was filled partially by injection (i.e., 75% of the full shot) and foaming was induced later by releasing the gas from the mold cavity and mold opening. Figure 5.1(a) shows the sequences of the steps for a full injection cycle and the level of the desired cavity pressures. As Figure 5.1b shows, mold cavity pressures were also measured at three different
locations: near the gate, the middle of the cavity, and near the end of the cavity for the entire injection cycle using three PT462E Dynisco pressure transducers and a DAQ board (Compact DAQ Kit, National Instruments) to ensure that the desired pressures were achieved at each phase of the entire process.
Figure 5.1: (a) Designed cavity pressure profile for foam injection-molding, and (b) a schematic drawing showing the locations of the pressure transducers in the mold cavity.

The unit for all the dimensions is in millimeter.

Table 5.1 summarizes the fixed and varied foam injection-molding parameters. The optimum values for the fixed parameters were first determined by a series of trial and error experiments. With a short delay (about 2s) after the polymer melt was injected into the cavity, the mold was opened enabling the cells to grow. An optimized delay was intended to allow the skin of the injection-molded part to be solidified before opening the mold to maintain structural integrity. Avoiding or shortening the delay time resulted in non-flatness of the skin of the injection-molded parts. Longer delays produced a thicker solidified skin, which was not suitable for obtaining high expansion ratio foams and creating foam cavities.

**Table 5.1: Fixed and varied parameters in the injection molding of acoustic foams.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot size (cm³)</td>
<td>39 (75% of full shot)</td>
</tr>
<tr>
<td>Barrel pressure (MPa)</td>
<td>19</td>
</tr>
<tr>
<td>Gas injection pressure (MPa)</td>
<td>24</td>
</tr>
<tr>
<td>Screw speed (rpm)</td>
<td>300</td>
</tr>
<tr>
<td>Metering time (s)</td>
<td>8</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Injection flow rate (cm³/s)</td>
<td>100</td>
</tr>
<tr>
<td>Gas counter-pressure (MPa)</td>
<td>6 MPa</td>
</tr>
<tr>
<td>Delay in mold opening (s)</td>
<td>2</td>
</tr>
<tr>
<td>Degree of mold opening (mm), variable</td>
<td>0, 1.5, 4.5, 9, 12, 15</td>
</tr>
<tr>
<td>Mold temperature (°C)</td>
<td>35</td>
</tr>
<tr>
<td>N₂ content (wt. %)</td>
<td>0.8</td>
</tr>
<tr>
<td>Processing temperature (°C)</td>
<td>220</td>
</tr>
</tbody>
</table>

The polymer melt was injected into the cavity at the maximum capacity of the injection-molding machine for a flow rate of 100 cc/s throughout the process. A high flow rate resulted in a high shear rate, and consequently, the cells were elongated in the flow direction. The degree of mold opening was determined as the most influential parameter on the final structure of the expanded samples and thus varied to investigate its effects on the overall structure, the foam morphology and the acoustic behavior of the injection-molded samples. Other parameters were kept unchanged in all of the experiments.
5.2.2. Foam Characterization

The foam density ($\rho_f$) was measured using the water-displacement method (ASTM: D792-08 [http://www.astm.org/Standards/D792.htm]), and the relative density ($\rho_N$) or expansion ratio was calculated as the ratio of the measured density of the foam sample ($\rho_f$) and the density of the corresponding unfoamed material ($\rho_s$). To measure cell size and density, the samples were freeze-fractured and then coated with platinum using a sputter coater. The microstructures were then examined using a scanning electron microscope (SEM), JEOL JSM-6060. The image processing was carried out using ImageJ software, developed by the National Institutes of Health, US. The cell density was calculated from a micrograph and using the equation

$$cell\ density = \frac{nM^2}{A} \rho_N$$

(5.1)

where $n$ is the number of voids in the micrograph, $A$ is the area of the micrograph, and $M$ is the magnification factor of the micrograph. The open-cell content of foams was measured using a gas pycnometer (Quantachrome Instrument UltraFoam 1000) in accordance with the ASTM D6226-10 [http://www.astm.org/Standards/D6226.htm].

5.2.3. Perforation

Figure 5.2 shows the developed mechanized perforating apparatus used with injection-molded foams. An oven was heated by an embedded electrical element, which was connected to a programmable temperature controller (TC). The perforator was rotated by a DC motor equipped with a rotational speed controller. The oven was heated to the melt temperature of the polymer, and the sample was placed between the roller and the mechanical perforator. The
proper perforation of the samples was carried out by tuning the rotational speed, the temperature and the gap between the roller and the perforator by nub screws.

![Figure 5.2: Developed mechanized perforating setup for injection-molded foams](image)

**Figure 5.2: Developed mechanized perforating setup for injection-molded foams**

### 5.2.4. Acoustic Property Characterization

The injection-molded acoustic foams were evaluated for their acoustic behaviors, i.e., the absorption coefficient and the transmission loss. The absorption coefficient represents the amount of absorption that a sound wave has when it hits the acoustic fence. The transmission loss represents the energy that the sound wave loses when it passes through the acoustic fence. According to the concept of acoustic attenuation, the absorption coefficient refers to a fraction of the sound wave that may be observed when the sound wave hits the sample, and it varies from 0 (no attenuation) to 1 (100% attenuation). The term “transmission loss” also refers to the lost
decibels of sound wave power when the wave passes through the sample, and it can vary from 0 to any value.

The transmission loss and absorption coefficient of the samples were measured using an impedance tube and the Tube-X™ utilities package in accordance with the ASTM E1050 – 12 http://www.astm.org/Standards/E1050.htm. The Tube-X™ utilities package was able to account for the effects of the temperature, the barometric pressure, and the attenuation of the measured quantities [12].

5.3. Results and Discussion

5.3.1. Structure and Cellular Morphology of Acoustic Foams

Table 5.2 gives the sample number, the mold opening length, and the final thickness of the injection-molded acoustic foams. Two different types of structures were made in the acoustic foams. The PP1, PP2 and PP3 samples were made without an internal cavity, but a cavity was introduced in the middle of the PP4, PP5 and PP6 samples. The cell morphology, the expansion ratio, the open-cell content, and the acoustic properties of these two types of acoustic foams are discussed in the next sections.

Table 5.2: Sample number, degree of mold opening and final thickness of the injection-molded acoustic foams

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mold opening</th>
<th>Final thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number</td>
<td>length (mm)</td>
<td>(mm)</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>Acoustic foams without internal cavity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP1</td>
<td>0</td>
<td>3.2</td>
</tr>
<tr>
<td>PP2</td>
<td>1.5</td>
<td>4.7</td>
</tr>
<tr>
<td>PP3</td>
<td>4.5</td>
<td>7.7</td>
</tr>
<tr>
<td>Acoustic foams with internal cavity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP4</td>
<td>9.0</td>
<td>12.2</td>
</tr>
<tr>
<td>PP5</td>
<td>12.0</td>
<td>15.2</td>
</tr>
<tr>
<td>PP6</td>
<td>15.0</td>
<td>16.5</td>
</tr>
</tbody>
</table>

5.3.1.1. Acoustic Foams without Cavity

PP1, PP2 and PP3 samples were fabricated by filling 75% of the pressurized cavity during the injection cycle and the full-length samples were created by expansion during foaming. Figure 5.3 shows the SEM micrographs and schematic structures of the PP1 and PP2 acoustic foams. Three distinguishable regions were identified across the thicknesses of the PP1 and PP2 samples, namely the skin layer, the transition layer, and the core region. As expected, the skin layer had a
non-foamed solid structure due to the very rapid solidification of polymer in this region. Both the transition and core regions were foamed but with different cellular morphologies. As the inserts of Figure 5.3a show, the core region of the PP1 sample had relatively uniform spherical cells while the cells in the transition layer were highly elongated. Ameli et al. observed similarly constructed layers with different cellular morphologies in polylactide samples that were injection-molded at a high flow rate [13]. It is believed that close to the skin the polymer melt had a lower temperature than at the core and that this lower temperature, coupled with a high injection flow rate, induced greater shear stresses in the transition region. This resulted in more elongated cells in this area.

When the injection of the melt/gas mixture into the mold cavity was followed by a timely mold opening, the cells were provided an opportunity to grow further, specifically in the sample thickness direction and this resulted in the acoustic foams with larger cells. Figure 5.3b shows the SEM micrographs and a schematic structure of the PP2 foam made with 1.5 mm of mold opening. Similar to the PP1 sample, three distinct layers of skin, transition, and core were also observed in the PP2 sample. However, cells in the PP2 sample were further expanded in the thickness direction and thus the severity of their elongation in the machine direction was decreased.
Figure 5.3: SEM micrographs and schematic structures of acoustic foams made (a) without mold opening (PP1) and (b) with 1.5 mm length of mold opening (PP2).
Opening of the mold enhanced cell growth in the thickness direction in both the transition and core layers. It is, however, believed that the mechanisms of cell growth in these two layers were different. The cells in the transition region were elongated in the machine direction because of the shear, and were in an unstable state [14-15]. Due to low melt strength of the material used and high shear, a lot of cell coalescence has taken place in the transition region [16-17]. Through the space provided by the mold opening, these cells tried to reform into spherical shapes by growing further in the thickness direction. Due to the low temperature, the cell shape in the transition region will be determined by the amount of mold opening. In the core region, however, due to the relatively high temperature of the polymer melt, the cells expanded uniformly in every direction meaning that, they had spherical growth rather than unidirectional growth.

To study the effect of further degree of mold opening, the PP3 sample was produced with 4.5 mm of mold opening length. Figure 5.4 shows the cellular morphology of the PP3 acoustic foam. At this degree of mold opening, the severity of cell elongation was greatly improved and relatively spherical cells were created in both the transition and core regions. In the PP3 sample, the cells had enough space to grow in the thickness direction and thus the cells that had initially elongated in the length direction now became spherical. Therefore, it can be concluded that the application of an optimum degree of mold opening can result in a cellular morphology with relatively uniform and spherical cells.
Figure 5.4: SEM micrographs of foam produced with 4.5mm mold opening length (PP3).

Figure 5.5 shows the expansion ratio and open-cell content of the PP1, PP2 and PP3 samples. While cells in the PP1 sample expanded due to the partial filling of the mold cavity (i.e., 75% of full shot) and to the polymer shrinkage that occurred during cooling, in the PP2 and PP3 samples the cells expanded additionally as a consequence of the mold opening. The expansion ratio for the PP2 and PP3 samples was proportional to the mold opening length. Almost no open cells were observed in the PP1 foam. This was due to the low expansion ratio, the thick cell walls, and the small cell size [18-19]. In the PP2 foam, with three times the expansion ratio, only 12% of the cells were interconnected. However, in the PP3 foam, many cells were interconnected and an open-cell content of about 67% was obtained. SEM micrographs of PP3 (Figure 5.4) revealed that the interconnection of the cells in this foam was through the creation of the pin holes. And these were caused by the induced shear on the cell walls as well as by the shrinkage of the cell walls that occurred due to solidification during the mold opening. McRae [20] showed that foam with an open-cell content of about 70% may
contribute significantly to acoustic properties in a frequency range of 500-5500 Hz. Chi et al. [21] recently fabricated poly (ethylene oxide) PEO/NaCl/hydroxyapatite (HA) composite porous material using injection molding with an open-cell content of 67%. However, such a high content of cell-opening has not yet been reported for neat polypropylene.

![Graph showing open-cell content and expansion ratio](image)

**Figure 5.5**: Open-cell content and the expansion ratio of the acoustic foams without cavity.

### 5.3.1.2. Cavity-integrated acoustic foams

Figure 5.6 shows the procedure of fabricating cavity-integrated acoustic foams using the foam injection-molding process equipped with a mold opening technique and mold cavity gas counter-pressure. The cells were nucleated during the injection and filling stages. When the mold was opened, the cells grew up to a certain degree of the mold opening, beyond which a crack was initiated inside the hot core of the foams, which created the cavity. It is believed that crack initiation strongly depends on the speed of the mold-opening. While fast mold-opening facilitates
early crack initiation, slow mold-opening postpone or even prevent from crack initiation. In addition, it is believed that crack initiation depends on the cell nuclei density, the amount of gas, the resin kind, the additive kind, the melt temperature, the mold temperature, and etc. This matter is not easy to be modeled since it has complicated phenomena including the heat transfer, the mass transfer, the bubble nucleation and growth, crack nucleation and growth, etc.

**Figure 5.6:** A schematic representation of the creation of the cavity inside the injection-molded foams using a mold opening technique: (a) foamed sample right after the injection, (b) crack initiation while the mold was opening, and (c) the final cavity created in the core.

Figure 5.7a shows the cross section of the overall structure of the cavity-integrated acoustic foam PP5 sample, including the skin region, the foamed region, and the internal cavity. Figure 5.7b also depicts the cellular morphology of the PP5 sample. Similar structures, but with different cavity depths, were observed for the PP4 and PP6 samples as they were fabricated using a different mold opening length. Figure 5.8 shows the thickness of the cavity and the surrounding foamed regions. The cavity depth increased significantly with an increased mold opening length. However, the thickness of the foamed region on both sides of the cavity increased only slightly.
with increases in the opening lengths of the PP4, PP5 and PP6 samples. At the instant that the crack was initiated in the middle of the foamed region, the foam expansion was terminated and the cavity depth increased.

Figure 5.7: (a) A photograph of the PP5 sample showing the cross section of the overall structure including the skin region, the foamed region, and the internal cavity, and (b) a SEM micrograph of the PP5 sample showing the cellular morphology of the foamed region.
Figure 5.8: The average thickness of the cavity and the surrounding foamed region for cavity-integrated acoustic foams in the PP4, PP5 and PP6 samples.

Figure 5.9 shows the open-cell content and the expansion ratio of the cavity-integrated acoustic foams in the PP4, PP5 and PP6 samples. All of the samples had an average expansion ratio and an open-cell content of about 70% and 4.5, respectively. All other foam injection-molding parameters were kept the same for these three foams, and only the mold opening length was varied. It is plausible to assume that after the crack initiation in the middle of the foams during the mold opening, no further cell growth or pinholes occurred in the foamed regions. Consequently, the foamed regions of all three samples presented relatively similar expansion ratios and open-cell content.
Figure 5.9: Average open-cell content and expansion ratio of the cavity-integrated acoustic foams produced.

The SEM micrographs of the samples with cavity (i.e., PP4, PP5, and PP6) showed that the cells close to the skin layer were much smaller than other cells. This was due to the fact that the early solidification of the melt in the regions close to the skin layer hindered cell growth. The cells in areas farther from the skin were all well expanded and their cell walls became thin. Most of these cells were interconnected by pinholes. Figure 5.10 shows a SEM micrograph and the cell size distribution for the PP5 sample. Similar trends were observed for the PP4 and PP6 samples. While cells near the skin layer were about 20 μm, all the cells located at a distance of more than one mm from the skin layer had an average size of about 130 μm. It was difficult to measure the variation of the expansion ratio of the foams across the thickness. However, it is believed that a trend similar to that of the cell size would also exist for the expansion ratio.
5.3.2. Pressure Profiles in the Mold Cavity

The pressure profile (Figure 5.1) for the mold cavity was designed to maintain the required pressure on the melt to avoid premature cell nucleation and growth during the injection and filling stages. It was also intended to enforce uniform pressure of the melt in the entire cavity. A uniform pressure profile within the entire cavity is a necessary requirement in order to ensure uniform pressure drop and pressure drop rate and thus to achieve a fairly uniform cell nucleation and growth and consequently a uniform cell morphology within the entire sample [22]. Using three pressure gages, the pressure of the melt was recorded in three different cavity locations: (A) near the gate, (B) in the middle, and (C) near the end of the cavity, as Figure 5.1a shows. The recorded pressures at these three locations are noted in Figure 5.11. It is seen that nearly identical pressure profiles could be imposed on each of these locations.
5.3.3. Acoustic Properties

In panel-type sound absorbers, the resistance of the front panel for fast shaping attenuates the energy of the sound wave. This attenuation depends strongly on the mass of the panel. It has been shown that each time the panel mass is doubled its transmission loss improves by 6dB. Thus, the small expansion of the foam close to the skin layer area would increase the skin layer mass and result in a higher transmission loss [23]. On the other hand, an open-cell structure with a relatively large cell size in other foam areas would improve the absorption coefficient of the foams [23]. In addition, the existence of an air-gap in the middle of the samples would further improve the transmission loss and absorption coefficient of the samples [24]. Therefore, the

Figure 5.11: Recorded pressure profiles near the gate, the middle and the end of the mold cavity.
structural pattern of cavity-integrated acoustic foams that included the following features would be an effective design for efficient sound insulation: (i) a solid and dense skin layer, (ii) a foamed region with a gradually increasing cell size and an expansion ratio from the skin layer toward the core (i.e., decreasing density) along with the creation of open cells, and (iii) a cavity in the middle of the sample.

Figure 5.12 shows the absorption coefficient of the acoustic foams in a frequency spectrum of 400-1600 Hz. The acoustic foams without cavity (i.e., PP1, PP2 and PP3 samples) showed no wave attenuation. However, the cavity-integrated foams (i.e., PP4, PP5 and PP6 samples) demonstrated a high absorption capacity in the tested frequencies spectrum. The absorption coefficient for the PP1 and PP2 samples was quite minor, even though some fluctuation was observed. It is believed that zero absorption coefficients occurred for two reasons: First, because the PP1 and PP2 samples lacked open-cell foam; and second, because their foam structure was solid due to low foam expansion. Fluctuations in the absorption coefficient around zero was an artifact of the noise and cannot be considered a result of wave absorption. The PP3 sample showed an absorption coefficient of about 0.3 at a frequency of 800 Hz, which should have resulted from the higher expansion ratio of the foam and the higher open-cell content of the PP3 sample, compared with the PP1 and PP2 samples.
Figure 5.12: Absorption coefficient results for the acoustic foams.

Compared to the acoustic foams without cavity, the absorption coefficients of the cavity-integrated foams, i.e., PP3, PP4, and PP5 samples, were significantly higher. The improved sound insulation behavior that resulted is attributed to the cavity created inside these samples. Peak frequency absorption for some sound absorbers is critical [23-24]. Many devices are generating a high amount noise in a relatively short range of frequencies, and for designed absorbers for these devices dissipating their noise in their peak frequency noise is a big requirement [1]. As the cavity depth increased from the PP4 to the PP6 samples, the absorption coefficient, as well as the corresponding peak frequency, increased. Peak absorptions of around 0.65, 0.83 and 0.95 were observed for the PP4, PP5 and PP6 samples, respectively, with the corresponding peak frequencies of 950 Hz for PP4, 1040 Hz for PP5 and 1180 Hz for PP6. The significance of these results relates not only to obtaining high peak absorption, but also to the
frequency spectrum. Kim et al. studied the noise frequency spectrums that existed in such varied locations as a hospital, a school, residential and commercial areas, and semi-industrial areas. Their studies showed that the noise peak frequency in almost all of these areas was around 1000 Hz [25]. Further, the world health organization (WHO) has warned that noise with such a large proportion of low frequency components may increase health risks significantly [26]. Zulkifli et al. [27] obtained a peak absorption coefficient of about 0.95 for a 20 mm coconut coir fiber panel in a frequency of 3700 Hz. However, for a frequency range of 400-1600 Hz, they reported an absorption coefficient of about 0.1-0.5, which is significantly lower than those obtained here for the cavity-integrated acoustic foam PP5 and PP6 samples with 15.2, and 16.5 mm of thickness, respectively.

It has been shown that perforating the front panel of multi-layer acoustic foams may improve their attenuation behavior [28-29]. To examine the effect of perforation on the cavity-integrated acoustic foams, one side of the PP4, PP5, and PP6 samples was perforated using the perforating system as shown in Figure 5.2. After perforating PP4, PP5, and PP6 were renamed PP4AP, PP5AP, and PP6AP respectively. Absorption coefficient of the perforated cavity integrated foams is also shown in Figure 5.12. The obtained results proved that perforation has raised the absorption properties of the foams significantly. As Figure 5.12 shows, although the peak absorption coefficient did not vary after the perforation, it spanned a much wider range absorption frequency. The improvement on the absorption of the samples after perforation is shown on Figure 5.13 for the foams with different cavity lengths.
Figure 5.13: Improvement on the absorption coefficient because of the perforation for the sample with different cavity length.

Figure 5.14a shows the variations of transmission loss in the injection-molded acoustic foams and their frequencies. Overall, all the samples presented similar trends with respect to frequency. The transmission loss first decreased with the frequency increasing up to about 550 Hz. Then the transmission loss started to gradually increase with frequency. The low peak transmission loss for the samples around 550Hz represents their mass-air-mass resonance frequency [30-31]. The increase in transmission loss with increased frequency is due to the mass and frequency effect [30-31]. Figure 5.14b shows the average transmission loss of the samples in a frequency range of 600-1600 Hz. It was observed that the thicker samples had a higher transmission loss. While an average transmission loss of 28.1 dB was observed for the PP6 sample, an average transmission loss of 16.1 dB was recorded for the PP1 sample.
An average transmission loss of 16.7 dB and 18.7 dB was observed for the PP2 and PP3 samples, respectively. While there was only a 0.6 dB increase in the transmission loss when the mold was opened 1.5 mm in the PP2 sample, the increased transmission loss was 2 dB when an additional 3 mm of mold opening was introduced to fabricate the PP3 sample. We surmise that the significant increase in the transmission loss for the PP3 sample was due to its high open-cell content (Figure 5.5). Figure 5.14b also shows that the transmission loss significantly increased with the cavity depth in the cavity-integrated foams. The average transmission loss was measured to be 21.6 dB, 24.3 dB, and 28.1 dB for the PP4 (6 mm cavity depth), the PP5 (8.4 mm cavity depth), and the PP6 (9.3 mm cavity depth) samples, respectively. Since similar cell morphology was obtained for all of these samples, the attenuation improvement was attributed to the existence and size of the air cavity.
Figure 5.14: (a) Transmission loss versus frequency and (b) the average transmission loss of the acoustic foams.

5.4. Conclusions

A novel strategy was developed to produce cavity-integrated acoustic foams. A mold opening technique with a tuned foam injection-molding processing condition was used in which cells were highly expanded and their walls became thinned. High shear stresses were applied to the cells during cell growth and elongation. The cell walls also experienced additional shear stress when they started to solidify. By applying a high shear to the thinned cell walls, pinholes were created in them, which interconnected the cells and produced an open-cell structure. A maximum expansion ratio and an open-cell content of 4.6 and 67%, respectively, were obtained for the injection-molded acoustic foams.
By opening the mold further followed by initiating a crack, cavities were successfully created inside the foams. The cavities significantly enhanced the absorption coefficient of the acoustic foams and the absorption coefficient was increased by the increased cavity depth. Cavity-integrated foams presented a peak absorption coefficient of 0.65 to 0.95 in a frequency range of 950-1200 Hz. The effect of perforation on the absorption coefficient was also studied using a mechanized perforating system. The perforation widened the frequency range of the maximum absorption coefficient. The transmission loss of the injection-molded acoustic foams was also measured, and it was found that the transmission loss was proportional to the thickness of the samples. While a maximum transmission loss of about 41 dB was observed for the sample with 16.5 mm of thickness (PP6), a transmission loss of 26 dB was obtained for the sample with 3.2 mm of thickness (PP1). This investigation revealed that cavity-integrated multi-layer acoustic foams with efficient sound insulation can be fabricated in a cost-effective manner, and that this can be done through a foam injection-molding process that uses mold opening.
5.5. References


Chapter 6: Development of High-Performance Micro-Perforated Panels (MPPs) for Low-Frequency Sound Absorption

6.1. Introduction

While technology development has accelerated in the last two decades, the development of sound insulation has not been considerable [1-2]. Research has shown that elevated sound levels may cause hearing impairment, hypertension, ischemic heart disease, irritability, and sleep disturbances [3-4]. While the frequency spectrum of most noise ranges from 400 Hz to 1500 Hz
the sound insulation techniques effective for this range are limited. Porous polyurethane foams, which dissipate sound waves through thermal conduction and viscosity, have commonly been used in industry and in building construction. These foams are effective in the high frequency noise spectrum [7-8], but for low frequency noise, a thicker layer of them is required. Multi-layer sound insulating materials constructed with massive front panels, air-cavities, and highly porous materials, are used in many applications in the automotive, aviation, and building construction sectors. But they are complicated to analyze, and in some applications they are not economical. The simplicity of the micro-perforated panels (MPPs) and their efficiency in low frequency insulation has attracted much attention [9-10].

Recently, MPPs constructed with a perforated thin plate and backed with a cavity have been seen as a promising sound insulation system [9, 11]. The MPPs’ thin plates have a sub-millimeter thickness (normally 0.5-2 mm) and are made from different materials, including polymers [12]. The length of the cavity varies with the application type and the frequency spectrum range. The perforation ratio and size are also varied in a wide range for different applications [13]. Our study includes these variations and was carried out on MPPs to improve their acoustic behaviors by foaming the thin plate that the sound insulating systems use.

6.2. Hypothesis

It has been found that most MPP sound wave dissipation takes place in the panel’s perforations in the low frequency spectrum (below 1,500 Hz)[14]. Figure 6.1 illustrates the mechanism of sound wave dissipation in MPPs. The sound wave has a compression and rarefaction region, and when the compression locates close to the perforations, it pushes the air particles inside of the cavity through them. And when the compression of the sound wave
replaces with the rarefaction, air particles are pushed out from the cavity. The air particles have a moment of inertia that helps to stabilize the pressure fluctuations, and this causes a longer displacement of the air particles. The movement and vibration of the air particles in the perforation is repeated with the magnitude of the sound wave frequency. And each time that the air particles go out or in, they experience some resistance from the perforations’ walls. The vibration of the air particles in the perforations along with the resistance from the perforations’ walls dissipate the sound energy.

Figure 6.1: Sound wave dissipation mechanism using Helmholtz resonators.

The solid thin plate used in the conventional MPPs was replaced with a foam thin plate to try to improve its acoustic behavior. Figure 6.2 shows the mechanism for improvement of its acoustic behavior by foaming. Figure 6.2(a) shows a schematic of currently available MPPs with a solid thin plate and Figure 6.2(b) shows the proposed MPP system with a foam thin plate. In the proposed system, the thin plate is uniformly foamed. The perforations that result have some roughness on the cell walls, unlike those using the solid thin plate. This roughness can resist the flow of the sound wave and possibly result in larger sound wave dissipation than those using the
thin plate. Further, the number of air particles vibrating in the perforations of a MPP with foam thin plate is larger than those in the solid plate because of existence of voids in foam plate. And this is another reason for sound wave dissipation using proposed system. The intention of our study was to achieve a foam with a cell size significantly smaller than the perforation size. We also aimed for, a higher cell density to provide a higher and smoothly flowing resistance to sound waves.

Figure 6.2: (a) A schematic of a currently available MPP with solid thin plate, and (b) the proposed MPP system with a foam thin plate.
6.3. Experimental Procedure

6.3.1. Materials

The commercially available injection molding grade of polypropylene (PP), Certene PHM35 was used. It was provided in a pellet form and had a specific gravity of 0.903 g/cm³, a melt flow index of 35 g/min., and a Vicat softening temperature of 152 °C. The nucleating agent, talc (grade Cimpact CB710), was provided by Luzenac. It had a density of 2.8 g/cm³ and an average particle size of 1.7 µm. Carbon dioxide (CO2) was supplied by Linde Gas, Canada and was used as the physical blowing agent.

6.3.2. Sample Preparation

It is challenging to foam a thin injection-molded part. Compared with thick parts, a limited void fraction and cell density are obtainable because of the limited cavity space for cell growth in the thin parts. A narrow window of processing temperature, gas content, residence time, and pressure drop rate would result in a favorable foam cell morphology. Since polymer melt solidifies relatively fast, the complete filling of the mold cavity would require a higher melt temperature, a higher injection flow rate, and/or a high injection pressure [15-17]. However, each of these actions can cause undesirable conditions during the molding process. A high injection flow rate causes an undesirable melt fracture in the polymer. Excessively high melt temperatures can result in thermal degradation of the polymer and in excessive shrinkage and warpage. These, in turn, affect the dimension stability, the cell morphology and the mechanical properties of the molded parts [18-19].
Very few studies have been reported on the foaming of thin injection molded parts. But the microcellular foaming of thick (that is, more than 3 mm) injection molded parts has been extensively studied in the last few years. For thick parts, it was found that a finer cell structure and a more uniform cell size distribution could be achieved by controlling the absolute pressure and pressure gradient at the mold gate [20, 21]. Microcellular and relatively fine-cell structures have been successfully produced for thick injection molded parts [22-23]. However, Swett [24], Loar [25] and Wang [26] are the only researchers who have discussed foaming thin parts. Regrettably, with the exception of Wang’s work, their achievements were empirically limited. Wang studied the effects of two different fan gates and two different edge gates in foaming 1 mm injection molded parts. He determined that a 1 mm fan gate enhanced the complete filling of the cavity due to the low flow resistance of this gate. Further, he concluded that a 1 mm fan gate provided better cell morphology in terms of cell density and a fine-cell size because it provided a more equal pressure distribution throughout the cavity. However, Wang did not study the cell morphology and uniformity of produced foams, and his published SEM pictures illustrated a 50-100µm cell size. In this work, a study was conducted for the uniform foaming of thin plates, and a cell size of 15 µm was intended. Foam thin plates were micro-perforated and used to construct MPPs. Finally, the acoustic behavior of MPPs was observed.

An advanced foam injection molding machine, shown in Figure 6.3, was used to produce both solid and foam 1 mm-thick polypropylene injection molded parts. It was modified from an 80-ton piggy-back injection molding machine produced by Sodick Plustech Inc. The introduction of a gear pump between the accumulator and the plasticizing barrel, which is responsible for continuously generating the single phase polymer/blowing agent (BA) solution, enabled a close monitoring of the pressure of the single phase melt mixture after the barrel and before injection.
The mold contained a rectangular cavity with a fan gate at one end. The cavity dimensions were 135 mm × 111 mm × 3.2 mm.

**Figure 6.3: Apparatus and method for advanced structural foam molding [27-28].**

Table 6.1 summarizes the fixed and varied foam injection molding parameters. The optimum values for the fixed parameters were determined by a series of trial and error experiments. The mold and the melt temperatures and the injection flow rate were determined as the most influential parameters on the final structure of the expanded samples. Thus, they were varied to investigate their effects on the foam structure. In all of the experiments, the other parameters remained unchanged.

**Table 6.1: Fixed and variable parameters in the foam injection molding of polypropylene.**
### Foam Structure Characterization

The foam density was measured either geometrically or by using the water-displacement method (ASTM: D792-08). The expansion ratio ($\phi$) was calculated using Equation 1.

$$\phi = \frac{d_s}{d_f}$$  \hspace{1cm} (6.1)

where $d_s$ and $d_f$ are the density of the unfoamed solid material and foamed sample, respectively.
To study their microstructure, the samples were freeze-fractured and then coated with platinum using a sputter coater. The microstructures were then examined using scanning electron microscopy (SEM), the JEOL JSM-6060. The cell density was calculated using Equation 2.

\[
\text{Cell Density} = \left( \frac{n}{A} \right)^{\frac{3}{2}} \phi
\]  

(6.2)

where \(n\) is the number of cells in the micrograph; \(A\) is the area of the micrograph. The open cell content (O.C.) of the foams was calculated using Equation 3.

\[
\text{O.C.} = (1 - \frac{V_a}{V_g}) \times 100\%
\]  

(6.3)

where \(V_a\) and \(V_g\) are the actual volume and the geometric volume of the foam, respectively.

### 6.3.4. Acoustic Property Characterization

Sound absorption coefficient is defined as the ratio of the sound energy absorbed by a surface to the sound energy incident upon that surface [29]. Accordingly, it may take on all numerical values between 0 and 1. In practice, the absorption coefficient at normal incidence \(\alpha\) is calculated using the normal surface impedance

\[
\alpha = 1 - \left| \frac{Z_n - Z_0}{Z_n + Z_0} \right| = 1 - |R|^2
\]  

(6.4)

with \(Z_0\) the impedance of the fluid domain defined as
\[ Z_0 = \rho_0 c_0 \] (6.5)

in which \( c_0 \) and \( \rho_0 \) are the sound speed in m/s and density of the fluid domain in kg/m\(^3\), respectively [30]. Sound absorption is computed if the excitation is plane wave. \( Z_n \) is normal surface impedance defined as the ratio of surface acoustic pressure to associated particle velocity. This definition makes sense when the surface acoustic pressure is fixed on the surface of the multi-layer elastic materials and the normal particle velocity is constant. Where these two parameters are not fixed, their average values are considered in the calculation.

MPPs using solid and foam injection molded parts were evaluated for their acoustic behavior (i.e. their absorption coefficient) using an impedance tube and the Tube-XTM utilities package in accordance with the ASTM E1050 – 12. The Tube-XTM utilities package was able to account for the effects of the temperature, the barometric pressure, and the attenuation of the measured quantities [31-32].

6.4. Results and Discussion

6.4.1 Foam Structure

To circumvent problems associated with the rapid solidification of the melt in the mold cavity, the mold was heated up to 80\(^\circ\)C, and the polymer melt was injected into the cavity at the maximum capacity of the machine (i.e. 400cc/c). Figure 6.4 shows the resultant foam samples at three processing temperatures, both with and without a nucleating agent. Even though the increased mold temperature helped to completely fill the cavity, it did not produce thin injection molded parts with a uniform foam structure. While the center of the injection molded parts had
been foamed, the tip area and the area right after the gate were not uniform. Our hypothesis is that at the area close to the gate, the melt temperature was relatively high. This would have lowered the melt strength of the polymer, resulting in cell coalescence and large voids [33-34]. Further, at all processing temperatures, some non-uniformity was observed in the samples’ tip area. This non-uniformity began some distance before the end of the part and continued on to the end. We believe that by the time polymer/gas mixture reached the end of the cavity that gas had escaped from the mixture. This commonly happens when the aspect ratio of the thin plate is too large and the presser on the melt is not uniform throughout the cavity. The width of this non-uniformity was increased by raising the processing temperature. This can be understood as the polymer melt strength’s dependency on temperature [35-36]. Finally, as Figure 6.4 clearly shows, the nucleating agent did not help to foam the thin injection molded parts that used a hot mold.
Figure 6.4: Foam injection molded parts produced by using a high-temperature mold (80°C), (a) With nucleating agent (talc), and (b) without nucleating agent (talc).

In an attempt to improve the uniformity of the foam thin injection molded part we tried using a moderate mold temperature. Figure 6.5 shows the foams produced using a moderate temperature mold at 40°C. It was clear that foam produced without a nucleating agent lacked uniformity. However, foam produced with a nucleating agent significantly improved foaming [37].
Figure 6.5: Foam injection molded parts produced using a moderate temperature mold at 40°C: (a) without nucleating agent and (b) and with nucleating agent.

To study the foams produced by using a nucleating agent in more detail, SEM micrographs of the samples were prepared in three locations: right after the gate, in the center, and at the tip of the samples, as Figure 6.6 shows. This confirms that in this processing condition the foams obtained were relatively uniform. However, this uniformity seemed more promising at a lower processing temperature.
Figure 6.6: SEM micrograph of the foam thin injection molded parts produced using a moderate temperature mold and talc as the nucleating agent.

The foams produced with 5% talc as the nucleating agent and with a mold and melt temperature of 40°C and 190°C, respectively, were chosen to construct MPPs and to perform the acoustic test. Characterizing these foams showed a 75% void fraction, 4E8 cell/cc cell density, and a 10µm average cell size.

6.4.2. Results and Discussions

Figure 6.7 shows the measured absorption coefficient for the MPPs constructed using solid (unfoamed) polypropylene injection molded parts in three cavity length of 30, 40, and 50mm,
while the perforations size is 200µm. In this figure “S” represents MPPs constructed using solid (unfoamed) parts. Also a number followed these two letters represents the cavity length.

Figure 6.7: Measured absorption coefficient for MPPs constructed using solid (unfoamed) polypropylene injection molded samples.

Following is the observation from absorption coefficient verses frequency curves for the three MPPs constructed using three different cavity lengths. 1) The absorption coefficient verses frequency curve for all the three MPPs has a mountain shape. 2) The peak absorption frequency for MPPs with 50mm, 40mm, and 30mm is 795, 915, 1005 Hz respectively. The peak absorption frequency decreased in increase of the cavity length. 3) MPP with a larger cavity length, showed higher absorption coefficient in 400Hz and lower at 1600 Hz. Hence, cavity length can be adjusted to bring the absorption frequency range to the favorite one as the requirement of an application.
Figure 6.8 shows the measured absorption coefficient for the MPPs constructed using foam polypropylene injection molded parts in three cavity length of 30, 40, and 50mm, while the perforations size is 200µm. In this figure “F” represents MPPs constructed using foam parts. Also a number followed these two letters represents the cavity length.

![Graph showing measured absorption coefficient for MPPs](image)

**Figure 6.8: Measured absorption coefficient for MPPs constructed using solid (foamed) polypropylene injection molded samples.**

Following is the observation from absorption coefficient verses frequency curves for the three MPPs constructed using three different cavity lengths. 1) The absorption coefficient verses frequency curve for all the three MPPs has a mountain shape. 2) The peak absorption frequency for MPPs with 50mm, 40mm, and 30mm is 700, 805, 975 Hz respectively. The peak absorption
frequency decreased in increase of the cavity length. 3) MPP with a larger cavity length, showed higher absorption coefficient in 400Hz and lower at 1600 Hz. Hence, for MPPs constructed with foam panel, the cavity length can be adjusted to bring the absorption frequency range to the favorite one as the requirement of an application.

Figure 6.9 shows the measured absorption coefficient for the MPPs constructed using foam and solid polypropylene injection molded parts in three cavity length of 30, 40, and 50mm, while the perforations size is 200μm.

Figure 6.9: Measured absorption coefficient for the solid and foam polypropylene injection molded samples.

Following is the observation when we compare the results for MPPs constructed with foam and solid panels. 1) The figures for foam and solid have the same shape and the trend of change on the absorption when frequency is changing is the same. 2) With foaming of the panel the peak
frequency of the absorption coefficient is moved toward lower frequency. 3) The value for the absorption coefficient at 400 Hz is significantly higher for the MPPs constructed with foam panel, however it is some lower at 1600 Hz. As absorption in lower frequency is usually more favorable for the industry, the improvement on absorption at low frequency by foaming of the panel in MPPs is considered a big advantage for foam MPPs. Figure 6.10 shows the improvement on the absorption coefficient when foam panel is used for constructing MPPs in 50, 40, and 30 mm cavity lengths. This calculation has been made for the frequency range of 400 Hz to the peak absorption frequency of the MPP with solid panels. Figure 6.11 shows the improvement when whole the test frequency (400-1600 Hz) is considered.

![Graph showing improvement in absorption coefficient](image)

**Figure 6.10:** Improvement on the absorption coefficient when foam panel is used for constructing MPPs in 50, 40, and 30 mm cavity lengths. This calculation has been made for the frequency range of 400 Hz to the peak absorption frequency of the MPP with solid panels.
Figure 6.1: Improvement on the absorption coefficient when foam panel is used for constructing MPPs in 50, 40, and 30 mm cavity lengths for the frequency range of 400-1600 Hz.

6.5. Conclusion

Foam and solid 1 mm-thick injection molded parts were produced using advanced foam injection molding machine. Produced samples were perforated in 200µm diameters using laser and MPPs were constructed using foam and solid panels. The absorption coefficient of the foam and the solid MPPs for different perforation sizes was measured using an impedance tube. This study revealed that by replacing the conventional MPPs with foam MPPs the absorption coefficient may be improved by 22% depending on the test frequency and considered cavity length.
6.6. References


Chapter 7: Prediction of the Transmission Loss for Injection Molded Acoustic Foams

7.1. Introduction

Injection molding is considered to be a reliable and feasible process and many parts for automotive, airspace, and medicine applications are produced using this process [1-3]. Foaming of injection molded parts not only lowers their weight significantly, but also gives them a unique mechanical and insulating property [4-6]. Our findings, presented in Chapters 4 and 5, has demonstrated that injection molded foams can be effectively used as sound insulating materials [7-9]. Novel methodologies to produce both three layer and five layer cavity integrated acoustic
foams were also presented. To provide relevant insights to the future development of the injection molded multilayer foams for sound insulation, this chapter presents a study on the prediction of acoustic property of the injection molded foams, which has not been done before.

The structure of multilayer acoustic foams produced by the injection molding process is different from others in many ways; hence, the methodology used for the prediction of the regular multilayer insulating materials [10-12] will not be suitable for the foams produced with the injection molding process presented in this thesis. For the injection molded foams produced in this thesis, there is always a skin layer, about 1mm in thickness, which covers the entire foam structure [13-14]. Although solid front panels have been used in multilayer structures to attenuate the sound wave, these front layers are typically made of rigid, high-density metallic materials, instead of plastics [15-17]. In addition, the cell morphology of the injection molded foams varies across the thickness direction, with cells close to the skin that are smaller than the cells in the core of the part [18-19]. This variation on the cell morphology is due to their inherent variation of the processing condition during the process. Another important difference in the structure of the multilayer acoustic foams developed by the injection molding process and other process is that in the injection molded parts, there is no physical interface between layers [20-21]. The interface effect in foams will be different. Any attempt to mechanically separate these layers for the evaluation of their acoustic properties may result in physical damage of the structure. Hence, it is of great interest to develop an empirical formula to model the sound insulation behaviors of the foams produced by the injection molding process.

7.2. Prediction of the Transmission Loss for Polycarbonate Foams
In Chapter 4, a novel methodology was developed to produce open-cell polycarbonate foams. Using the developed methodology, different polycarbonate foams were produced and they were characterized for sound insulation property. Injection molded open-cell foams may vary on open-cell content, thickness, density, cell size, and cell density [7-8, 22]. The structural tenability of injection molded open-cell foams conveys a huge potential for these foams to adapt them to specific applications including sound insulation. The insulation behavior of these foams can be optimized for a specific frequency range through close control of their cell morphology and thickness. In this thesis, the insulation behavior of 5 selected injection-molded polycarbonate parts were studied and Table 1 summarizes the information of the studied injection molded parts. As illustrated from Table 1, it is feasible to manufacture polycarbonate foams with different open-cell content and thickness through the injection molding process examined in this thesis.

<table>
<thead>
<tr>
<th>Sample#1</th>
<th>Average open-cell content (%)</th>
<th>Thickness (mm)</th>
<th>Relative density</th>
<th>Average cell size (µm)</th>
<th>Average cell density (Cells/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>3.2</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sample#2</td>
<td>3</td>
<td>5.8</td>
<td>0.55</td>
<td>42</td>
<td>1.3E7</td>
</tr>
<tr>
<td>Sample#3</td>
<td>10</td>
<td>8.9</td>
<td>0.36</td>
<td>63</td>
<td>9.3E6</td>
</tr>
<tr>
<td>Sample#4</td>
<td>77</td>
<td>12.3</td>
<td>0.26</td>
<td>115</td>
<td>2.7E6</td>
</tr>
<tr>
<td>Sample#5</td>
<td>82.5</td>
<td>16</td>
<td>0.2</td>
<td>163</td>
<td>8.2E5</td>
</tr>
</tbody>
</table>

Thickness of the material is considered one of the dominant factors in controlling sound insulation [23-26]. The thicker the materials are, the easier they are able to block the transmission of sound energy. Also, open-cell content of the foam is considered as a dominating factor in sound absorption [27-29]. Air particle (molecule) movement, by which sound wave energy is being conveyed, is resisted as particles propagate through the porous structure of the
materials. According to the results shown in Figure 7.1, Sample#5 has a transmission loss value of 55db at 1600 Hz, while the Sample#1 has a transmission loss value of 23.1db as the thickness and open-cell content of the foams were reduced from 16 to 3.2 mm and from 82.5 to 0%, respectively. Hence, it is of interest to develop a methodology to estimate the transmission loss of these foams based on their open-cell content and thickness.

In this thesis, we approached modeling the transmission loss of the polycarbonate foams by correlating it with the morphological structure of the foams. Equation 1 shows the empirical formula used for estimating the transmission loss (TL) for injection molded polycarbonate foams.

\[
TL(f) = a(f).T + b(f).OC + c(f).T.OC
\]  
(7.1)

In this formula, \( T \), and \( OC \) represent the thickness, and open-cell content of the foams, respectively and \( f \) represents the frequency of the sound wave. The parameters, \( a, b, \) and \( c \), are the coefficients associated with the thickness and open-cell content contributing in the transmission loss of the samples. They were considered to be frequency dependent, as the transmission loss of the developed samples were found to be considerably dependent on the sound frequency as shown in Figure 7.1.
There are three unknown parameters: a, b, and c in this equation that have to be defined.

Equation (7.1) can be rewritten in the following matrix format.

\[
\begin{bmatrix}
TL_1 \\
TL_2 \\
TL_3
\end{bmatrix}
= a \begin{bmatrix}
T_1 \\
T_2 \\
T_3
\end{bmatrix} + b \begin{bmatrix}
OC_1 \\
OC_2 \\
OC_3
\end{bmatrix} + c \begin{bmatrix}
T_1 \\
T_2 \\
T_3
\end{bmatrix} \begin{bmatrix}
OC_1 \\
OC_2 \\
OC_3
\end{bmatrix}
\] (7.2)

\[
AX = B
\] (7.3)

while

\[
B = \begin{bmatrix}
TL_1 \\
TL_2 \\
TL_3
\end{bmatrix}
\] (7.4)
Three test samples were required to calculate three unknown parameters, a, b, and c. Sample#3, Sample#4, and Sample#5 were selected for this calculation. The main reason for the selection of these three samples was their high capability in transmission loss attenuation due to their high open-cell contents and thicknesses. The other two samples, Sample#1 and Sample#2, which possess an open-cell content <3% were not considered for the modeling.

Table 7.2 summarizes the calculated values for a, b and c. After calculating the absolute values for a, b, and c, the best fitting curve was obtained for a, b, and c values and the following are the obtained fitting curve equations. The R-squared of the fitting curves for a, b, and c are 0.8925, 0.8515, and 0.8932 respectively.

\[
a(f) = 9E-19f^6 - 2E-14f^5 + 2E-10f^4 - 8E-07f^3 + 0.0019f^2 - 2.2929f + 1119
\]

\[
b(f) = -8E-18f^6 + 2E-13f^5 - 1E-09f^4 + 6E-06f^3 - 0.0132f^2 + 15.515f - 7248.4
\]

\[
c(f) = 6E-19f^6 - 1E-14f^5 + 8E-11f^4 - 3E-07f^3 + 0.0005f^2 - 0.5015f + 188.25
\]

**Table 7.2:** The a, b, and c values for PC samples
The transmission loss for the PC samples was calculated using equations (7.7), (7.8), and (7.9). Figure 7.2 shows the simulated and experimental results for Sample#3, Sample#4, and Sample#5. The estimation error for Sample#3, Sample#4, and Sample#5 was 0.25%, 0.26%, and 0.40%, respectively. As it is shown in the Figure 7.2, the simulated results match relatively well with the experimental results for Sample#3, Sample#4, and Sample#5 as anticipated, with minor variations between the simulated and measured transmission loss values. Figure 7.3 shows the simulated and experimental results for Sample#2, and Sample#1. The estimation error for Sample#1 and Sample#2, was 85.4% and 17.7%, respectively. For the Sample #1, the discrepancies between the simulated and experimental results are larger, which could be due to the fact that this sample was not a foam sample and its open-cell content was zero. For
Sample#2, the simulated transmission loss values were far from the experimental results. This could be due to the very low porosity of the foams.

Figure 7.2: Prediction and experimental results for transmission loss of the Sample#3, Sample#4, and Sample#5.
Even though the sample#2 has only 3% open-cell content, the simulated transmission loss is relatively close to the experimental results. This suggests that the defined equation is suitable for estimating the transmission loss of injection molded PC foams in this thesis.

7.3. Prediction of the Transmission Loss for Polypropylene Foams

Figure 7.4 shows the transmission loss for 6 injection molded polypropylene foams manufactured in this thesis. As described in Chapter 5, these polypropylene foams can be subdivided into two groups: Sample#1, Sample#2, and Sample#3 are three regular (without cavity) open-cells injection molded foams; Sample#4, Sample#5, and Sample#6 possess a cavity in the middle of the foams. Information of these foams is listed in Table 7.3.
Figure 7.4: Measured transmission loss for injection molded polypropylene foams

Table 7.3: Information of developed injection molded polypropylene foams

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Thickness (mm)</th>
<th>Open-cell Content (%)</th>
<th>Cavity Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample#1</td>
<td>3.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sample#2</td>
<td>4.7</td>
<td>0.09</td>
<td>0</td>
</tr>
<tr>
<td>Sample#3</td>
<td>7.7</td>
<td>0.65</td>
<td>0</td>
</tr>
<tr>
<td>Sample#4</td>
<td>12.2</td>
<td>0.73</td>
<td>6.0</td>
</tr>
<tr>
<td>Sample#5</td>
<td>15.2</td>
<td>0.70</td>
<td>8.4</td>
</tr>
</tbody>
</table>
As explained in Chapter 7.2., the open-cell content and thickness of the foams are the most dominant factors in determining the transmission loss. Hence the open-cell content and thickness of the foams were considered for the prediction of the transmission loss. Using Equation (7.1), the three unknown coefficients: \( a \), \( b \), and \( c \) were calculated. After calculating the values for \( a \), \( b \), and \( c \) the best fitting curves for them were obtained. The \( a \), \( b \), and \( c \) values for PP samples without a cavity and with a cavity are summarized in Table 7.4 and Table 7.5 respectively.

**Table 7.4:** The \( a \), \( b \), and \( c \) values for PP samples (without a cavity)

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>( a )</th>
<th>( b )</th>
<th>( c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>13.25</td>
<td>-116.42</td>
<td>38.11</td>
</tr>
<tr>
<td>450</td>
<td>10.82</td>
<td>-104.10</td>
<td>34.13</td>
</tr>
<tr>
<td>500</td>
<td>9.88</td>
<td>-100.56</td>
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**Table 7.5:** The a, b, and c values for PP samples (with a cavity)
For the PP sample without a cavity, equations for the best fitting curve for a, b, and c are as following. The R-squared of the fitting curves for a, b, and c are 0.9758, 0.5839, and 0.4682 respectively.

\[ a(f) = y = 2E-16 f^6 - 1E-12 f^5 + 3E-09 f^4 - 5E-06 f^3 + 0.0036 f^2 - 1.3988 f + 223.17 \] (7.10)

\[ b(f) = -1E-15 f^6 + 8E-12 f^5 - 2E-08 f^4 + 3E-05 f^3 - 0.0252 f^2 + 9.5223 f - 1505.7 \] (7.11)

\[ c(f) = 5E-16 f^6 - 4E-12 f^5 + 1E-08 f^4 - 2E-05 f^3 + 0.011 f^2 - 3.9959 f + 603.32 \] (7.12)

For the PP sample with a cavity, equations for the best fitting curve for a, b, and c are as following. The R-squared value of the fitting curves for a, b, and c are 0.6329, 0.5827, and 0.6063 respectively.

\[ a(f) = -4E-15 f^6 + 2E-11 f^5 - 6E-08 f^4 + 7E-05 f^3 - 0.0394 f^2 + 11.272 f - 1171.4 \] (7.13)

\[ b(f) = -5E-15 f^6 + 3E-11 f^5 - 8E-08 f^4 + 1E-04 f^3 - 0.0684 f^2 + 23.802 f - 3256.2 \] (7.14)

\[ c(f) = 7E-15 f^6 - 4E-11 f^5 + 1E-07 f^4 - 0.0001 f^3 + 0.0745 f^2 - 22.617 f + 2599.7 \] (7.15)

The transmission loss for all 6 injection molded polypropylene foams were simulated using the obtained values for a, b, and c and using Equation (7.1). The experimental and estimated results for the samples without a cavity are shown in Figure 7.5 and for the samples with a cavity are shown in Figure 7.6. For the samples without cavity errors of 3.9%, 1.2%, and 0.9% were observed for sample #1, sample #2, and sample #3, respectively. For the samples with a cavity: sample #4, sample #5, and sample #6 the error was 4.5%, 1.7%, and 4.8% , respectively. As it is
shown in Figures 7.5 and 7.6, estimated results fit the measured values relatively well. Hence, the results suggests that the obtained values for a, b, and c can be used to estimate the transmission loss of polypropylene foams with/without cavity manufactured from the injection molding process examined in this thesis.

Figure 7.5: Prediction and experimental results for transmission loss of the Sample#1, Sample#2, and Sample#3.
7.4. Effect of Materials on Transmission Loss

In this thesis, two matrix materials, polycarbonate and polypropylene, were examined in the manufacturing of multilayer acoustic foams with injection molding. It was interesting to examine the effect of the matrix materials on the transmission loss of the foam samples. Both PC and PP foams without a cavity, and similar structure of skin layer/foam/skin layer were observed; and any variation of the obtained values for a, b, and c may be considered as an indication on the material effect of transmission loss. Through comparing the obtained values of a, b, and c for PC foams, the following conclusions can be made for the results.

Figure 7.6: Prediction and experimental results for transmission loss of the Sample#4, Sample#5, and Sample#6.
1) The coefficient “a”, which corresponds to the thickness contribution of the samples for the transmission loss of the foams for polycarbonate and polypropylene foams, is relatively constant across the span of the sound frequency that was examined. This suggests that the sample thickness has a linear contribution to the transmission loss of both foams regardless of the test frequency. This is an interesting finding because the thickness can be used as an independent parameter for improving the transmission loss of the injection molded open-cell foams.

2) The obtained value for coefficient “b” varies with the sound frequency for both PC and PP foams. This observation may suggest that for both PC and PP foams, the influence of open-cell content on transmission loss is dependent on the sound wave frequency.

**7.5. Conclusion**

The process of foam injection molding is a very versatile tool to produce open-cell foams when it is equipped with a mold opening technique. A formula was developed for estimating the transmission loss of the injection molded open-cell foams (with/without cavity). Two of the most dominant properties of the open-cell foams, open-cell content and thickness of the foams were used to estimate the transmission loss. The results of the predictions were found to be feasible and promising.
7.6. References


Chapter 8: Conclusions and Recommendations

8.1. Summary of Major Contributions

In this thesis, we studied the acoustic properties of open porous foams and highlighted important parameters which affect the acoustic properties. We enhanced the injection molding process to develop open-cell foams and successfully manufactured injection molded open-cell foams. Their properties were tailored to produce highly insulation and absorption foams. A novel strategy was introduced to improve the acoustic behavior of MPPs.
8.1.1. Introduction and Background

Acoustic and noise control engineering along with foam materials was explained. Research motivation was presented. Current difficulties with developing acoustic foams and their environmental issues were explained. Furthermore, the objective of this thesis work was explained. And finally, the organization of the thesis was illustrated.

8.1.2. Development and Simulation of Acoustic Foams

Available methods for developing open porous material were presented. Also a summary of available methods on predicting absorption coefficient of open porous foams was given. Finally the performance of MPPs for absorption was explained and predicting the acoustic behavior of these systems was also presented.

8.1.3. Design of Open Porous Acoustic Foams

In order to understand the effect of the parameters on the acoustic properties of the open porous materials, open-cell foams in different porosity and different pore sizes were manufactured and analyzed. The absorption coefficients of the samples with different porosity and pore sizes were calculated. It was found that porosity has a dominant effect on the acoustic properties. Further, the effects of air-gap and thickness on the acoustic behavior were studied. It was found that the air-gap has a significant effect on lowering the absorption coefficient.
8.1.4. Development of Technology to Produce Open Porous Acoustic Foams Using Injection Molding for Insulation

A novel strategy was developed to produce highly expanded rigid polycarbonate (PC) foams with an open-cell structure. The foam injection-molding process was enhanced using a mold opening technique to achieve high expansion ratios. The cavity gas counter-pressure (GCP) method was also applied to improve the cell morphology and uniformity of the injection-molded foams. Their structure and expansion ratio were controlled by varying the degree of the mold opening. The structure, cell morphology, sound and thermal insulation behaviors, and mechanical properties of the foams were studied. The effects of several processing parameters on the foam structure were investigated, and the results showed that the degree of mold opening, melt temperature and injection flow rate were the most influential processing parameters in creating a cellular structure with a high open-cell content. A foam injection-molding process equipped with the mold opening and the GCP, together with tuned processing parameters, was able to successfully produce PC foams with expansion ratios as high as eightfold and open-cell contents of as high as 85%. The highly expanded foams increased the sound wave transmission loss by about 2.5 times and decreased the thermal conductivity by more than sixfold. This research shows that the foam injection-molding process can be effectively used in developing lightweight rigid foams for sound and thermal insulation applications.

8.1.5. Development of Air-Gap Integrated Acoustic Open-cell Foams for Absorption

A commercially available foam injection-molding machine was enhanced with a mold opening technique to produce polypropylene open-cell acoustic foams. Gas counter-pressure was used to improve the cell morphology and uniformity of the injection-molded foams. Their
structure and thickness were controlled by applying different degrees of mold opening. The sample structure, cell morphology, and acoustic behavior of the foams were characterized. A foamed structure with an open-cell content of 67% and an expansion ratio of 4.6 was obtained when the mold was opened by 4.5 mm. Although further opening of the mold did not significantly increase the open-cell content, it triggered crack creation in the middle of the foams, where the creation of cavities was also facilitated. The injection-molded foams with a cavity and a high open-cell content, presented remarkable acoustic properties: a peak absorption coefficient of 0.95 was observed for foam with a 73% open-cell content and a 9 mm cavity. An automated system was also developed to perforate the acoustic foams and the acoustic properties of foams both with and without perforation were studied. While perforating the foams widened their absorption coefficient frequency spectrum, it did not improve their transmission loss.

8.1.6. Development of a High-Performance MPP for Low-Frequency Absorption

MPPs that are constructed with a perforated panel and that are backed with a cavity are a promising sound insulation material for low frequency spectrum noise (i.e. below 1,600 Hz). In MPPs, vibration of the air in the perforations is the main reason for their acoustic damping. This work presents an innovative approach on improving the acoustic damping of the MPPs by foaming the perforated panel. In spite of the challenges inherent in foaming thin materials, 1 mm-thick polypropylene injection-molded foams were successfully produced using an advanced structural foam injection molding machine. A relatively uniform cell morphology resulted when the polymer melt was injected with relatively high pressure and a high flow rate. MPPs with a foam thin plate, showed a peak of 35% improvement on the sound absorption coefficient.
8.1.7. Estimation of the Transmission Loss for Injection Molded Acoustic Foams

A formula was developed for estimating the transmission loss of the injection molded open-cell foams (with/without foams). Two of the most dominant properties of open-cell foams, open-cell content and thickness of the foams were used to estimate the transmission loss. The results of the estimations were found to be feasible and promising. The developed formula can be used for optimizing acoustic properties of injection molded acoustic foams.

8.2. Summary of Major Contributions (Publications)

Invention Disclosure:


Refereed Journal Publications:


**Refereed Conference papers:**


### 8.3. Recommendation for Future Research

For the future of this research work, the following is recommended.

1) The model presented in this work to estimate the transmission loss of injection molding parts is suggested to be developed further to help explaining the acoustic behavior of injection molded open cell foams. This model can be used to optimize processing conditions in injection molding and improve the acoustic behaviors of multilayer injection molded acoustic foams.
2) Cell opening mechanisms and cell morphologies in the foam injection molding process are suggested to be investigated further. This will enable scientists to have closer control over the cell morphology and cell interconnections. Using a rapid heating and cooling mold could be very helpful in this study. It is believed that by optimizing the cell interconnections and the cell morphology, the acoustic properties of the injection molded parts could be improved significantly.

3) The multi-layer injection molded parts, the correlations between the properties of each layer (i.e. density, cell morphology, and thickness) and acoustic properties could be investigated further.

4) With the knowledge obtained in this work for the foaming of a thin plate and for developing foam micro-perforated panels systems, it is possible to conduct further research and development to improve the acoustic properties of these innovative materials. For example, the mechanism of absorption in foamed micro-perforated systems could be further investigated, and if possible a model for predicting sound absorption of these foamed micro-perforated panels could be developed.