Heat conductivity and permeability of aluminium foam

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Abstract. Aluminium foam is a material that structured by porous medium with certain characteristics such as good energy absorption, high heat conductivity and good heat transfer. These characteristics that aluminium metal foam provides, can be used in wide range of applications such as on heat exchanger, automotive and etc. The aim of this study is to evaluate the heat conductivity and permeability of the aluminium foam. The porosity of aluminium foam produced by NaCl replication are ranging from 60% to 75%. Besides, simulation by CFD software were carried out to compare with the effect of pore structure on heat conductivity and to determine the heat flux. At the end of the study, the heat conductivity value and permeability of the aluminium foam is better compared to solid aluminium when the temperature increased. The permeability of the aluminium foam is dependent on the porosity of the aluminium foam. Higher porosity resulting to a higher rate of permeability.

1. Introduction

Metal aluminium foam is a metal that which provides new point of view in engineering application. Because of its characteristics, the demand for this aluminium foam is increasing from time to time. The outstanding features that aluminium foam provides is the weight. Metal aluminium foam weight is light because of the foam structure and the porosity. The definition of porous materials is as a holey structure, which are mainly characterized by porosity. Foamed materials, which are the porous materials with high porosity and low density are, resemble bubbling materials such as soda and soap.

The holey materials which have porosity less than 70 %, are called porous materials [4]. Not only that, it strength also can be use in certain field of engineering which demands light but yet strong material. Because of the aluminium foam advantages, such as relatively high stiffness despite very low density, high corrosion resistance and etc., there is an increasing interest in using aluminium foams [11]. Metal foams are one of the most promising candidates for replacing traditional heat transfer augmentation techniques [3]. Recently, new research has found new method to manufacture aluminium foam with much less cost. Basically, the method is using NaCl as an agent holder to create the foam structure within the mold. The size of NaCl will determine the size of the porosity thus will also determine the permeability of the manufactured aluminium foam. This method is one of the recent method, and it still need to be explored thoroughly so a standard measurement can be determined.

These fabricated open cell-aluminium foam have different size of NaCl, ranging from 2 mm – 6 mm. Not only that, by using gas infiltration method are proven in creating a bigger size compared to
other methods available. In this research, the focus of aluminium foam application will be on heat exchanger in industries. Aluminium foam have been identified as a good material that can distribute and absorb heat to replace the commercial fin and tubes design. But a standard measurement and data are still not have been decided yet as it still in research and development progress. Furthermore, the cellular structure material such as foam and other porous material are known with the special physical and mechanical properties [10].

There are a lot of researches done to set a standard measurement for aluminium foam in term of its characteristics. The characteristics that relate to the researches are the permeability inside a vessel, the heat conductivity and the mechanical properties of the aluminium foam. If all the data successfully analyzed, the application of the metal can be widening, thus, increasing the demand in the future.

2. Methodology

2.1. Sample Preparation
Because of the size of the fabricated aluminium foam was ranging from 2.6 cm to 10 cm, the size of the sample cut down to the size of 2.5 cm diameter and 3 cm of height. The process started with using band saw to cut it in smaller size before go through the EDM wire-cut machine for detailed cutting. Then after that, the sample were polished as finishing touch before the experiment started.

![Figure 1. Sample of aluminium foam.](image)

2.2. Heat Conductivity Test
As discussed in the literature review, the same method of axial flow method machine was used to determine the heat conductivity. The thermal conductivity machine located in the Thermofluid Laboratory in Faculty of Mechanical Engineering, UiTM Shah Alam. Heater is controlled by the amount of power [Watt] input. Ranging from 0 W - 80 W, the apparatus can produce heat at almost to 190°C. For this experiment, the maximum heat input was set around 120°C - 130°C to prevent the machine from being overheat.

\[ Q = -kA \frac{dT}{dx} \] (1)
2.3. Permeability Test

By using the Constant Head Method, the experiment setup as close as to the actual experiment method. The experiment conducted in a simplified way. After the setup was done, the plain water was poured down into the funnel. The funnel was connected to the sample holder in order to channel the water to the water container underneath. With fixed amount of water poured, the time taken for plain water to drain gives different value between each sample. And also to determine the permeability for each sample. The equation 2 were used to determine the rate of permeability.

\[ K_{con} = \frac{\mu Q L}{\rho g h A \Delta t} \]  

\( (2) \)

2.4. CFD Simulation Analysis

The image from 2D surface 3 was converted to simplified 3D model. And the geometry would go meshing process and analysis process. From here, the preliminary data could be obtained and the rough assumption could be determined. Software ANSYS v15.0 was used for the simulation purpose. Using FLUENT setup, the heat flux obtained from the simulation was calculated in the heat conductivity formula. By far, the software yielding a closest result compare to the actual experiment conducted by P. Ranout et al. (2014). Therefore, this method was the best option compared to other CFD analysis software. The model design was based on the 2D view of the aluminium foam. Then it was projected to a certain length to make sure the model geometry was identical to the experimental specimen.

![Figure 2. Thermal conductivity machine.](image)

![Figure 3. Schematic diagram of 2D simulation.](image)
2.5. Electron Observation
The observation of the pore structure of the aluminum foam is conducted in the Research Laboratory at the Faculty of Dentistry, UiTM Sungai Buloh. The machine used is as shown in Figure 2 above.

3. Result and Discussion

3.1. Density and Porosity of Aluminium Foam
Depending on its porosity and density, the quality of the foam is determined from equation 3.

\[ \rho = \frac{m}{V} \]  \hspace{1cm} (3)

The total open volume of interconnected and isolated shape can be defined as the porosity. Porosity percentage is calculated by rough measurement of the open volume equal to 100% minus the part density.

\[ \% \text{ of porosity} = \frac{\rho_{Al} - \rho_f}{\rho_{Al}} \times 100 \]  \hspace{1cm} (4)

Where; \( \rho_{Al} \) = density of aluminium, \( \rho_f \) = density of foam.

| Sample | Mass [g] | Height [cm] | Volume [cm³] | Density [g/cm³] | Porosity [%] |
|--------|----------|-------------|--------------|----------------|--------------|
| 1      | 41.5540  | 3           | 14.726       | 2.82           | 0            |
| 2      | 14.8113  | 3           | 14.726       | 1.69           | 62.75        |
| 3      | 13.6093  | 3           | 14.726       | 1.78           | 65.78        |
| 4      | 14.4507  | 3           | 14.726       | 1.72           | 63.66        |
| 5      | 13.1689  | 3           | 14.726       | 1.81           | 66.88        |
| 6      | 15.0171  | 3           | 14.726       | 1.68           | 62.24        |
| 7      | 11.5271  | 3           | 14.726       | 1.92           | 71.01        |
| 8      | 14.8123  | 3           | 14.726       | 1.69           | 62.75        |
From the graph, aluminium foam sample number 6 is the highest porosity recorded with 71.01%. And sample number 5 is the least porous with 62.24%. Based on the measurement recorded, the expected heat conductivity of aluminium foam will be affected by porosity ranging from 62.24% to 71.01%. Referring to research done by S. Dawood and S.S.M. Nazirudeen (2010), metal foam which consists of 60% - 70% porosity will have the best attributes in terms of mechanical and thermal properties.

3.2. Heat Conductivity

The purpose of heat conductivity experiments is to determine the value of heat conductivity of aluminium foam with different porosity. By doing the experiment, the most suitable value of porosity with the best heat conductivity value can be determined. The value of $k$ can be obtained by using equation 1.

![Figure 5. Heat conductivity-heat input experimental result](image)

Based on the Figure 5, the value of heat conductivity, $k$ for all samples are high, some are exceeding 500 W/m∙K at the slightly above room temperature (32°C - 36°C). This is because of there is not enough heat or energy introduced in the sample, which cause the electron or molecule does not vibrate enough to transfer the energy. As the temperature increase, the heat conductivity decrease, this occurs because the molecular vibrations increase (in turn decreasing the mean free path of molecules). So, they obstruct the flow of free electrons, thus reducing the conductivity.

From research done by J.W. Paek et al. (2000), it is proven that the value of $k$ will be decreased when the porosity decreased. The obtained data from this experiment shows that even though the heat conductivity is affected by the porosity of the sample, at the same time it is also affected by variations in the cell size at fixed. Both experiments give out the similar outcome. Usage of aluminium foam of 60% - 70% porosity as heat conductor is better compared to solid aluminium.

Based on the result shown in Figure 5 also, the heat conductivity value is decreasing as the heat input increased. At the maximum heat input; i.e. 70 W, most of the sample of aluminium foam including aluminium ingot have reached their constant state. For aluminium ingot, the value is 226 W/m∙K. And as for the aluminium foam, the lowest heat conductivity value recorded at 70 W input is 150 W/m∙K with the porosity of 63.66%.

E. Sadeghi et al. (2011) stated that the effective conductivity decreases with an increase in porosity. However, the effect of pore density seems to be insignificant. Lower porosity values are associated with a higher volume of solid ligaments which provide high conductive paths for the heat flow.

3.3. Simulation Result

In this simulation, there were a few range of temperature used, as shown in Figure 6. The simulation done by ANSYS v15.0 was to indicate that a different structure of porosity will affect the heat
conductivity. There were three kind of shape that had been tested; Cylinders, Irregular and Ellipsoidal shape, as shown in Figure 7. All of the 3D model had the same porosity value at 60%. The heat input ranging from 94.4°C to 134°C with 20°C interval between. While the output was maintained throughout the simulation at 79.5°C.

![Figure 6. Heat conductivity-heat temperature simulation result.](image)

The output from this simulation was total surface heat flux. With the value obtained, then the calculation using simple heat flux equation to get the value of heat conductivity was conducted. All of the simulation value gave out the same decreasing trends. The higher the temperature, the lower the heat conductivity value until it reached leveling off value.

From the simulation done in the software, the value was different according to its porosity shape. The highest was the uniform circle and the lowest is the irregular or random shape. From that, it could be confirmed that how the shape coefficient value effect the thermal conductivity on a substance with same porosity level. By referring the theory that was introduced by Zehner and Schlunder (1970), it was proven that the porous structures play an important part in determining the value of heat conductivity.
Figure 7. (i) 2D drawing of cylindrical shape pore structure, (ii) 3D geometry of cylindrical shape pore structure, (iii) 2D drawing of ellipsoidal shape pore structure, and (iv) 3D geometry of irregular shape pores structure

3.4. Permeability Test Result

The permeability test is a measure of the rate of the flow of water through aluminium foam. In this test, water was forced by a known constant pressure through a aluminium foam specimen of known dimensions and the rate of flow was determined and recorded.

Figure 8. Experimental and numerical permeability result

Permeability are referred as the ease of water go through the porous medium. Based on Figure 8, it can be seen that the highest porosity drains the water the fastest. The expression for the permeability of replicated aluminium foam derived on the basis of the “bottleneck” model of a porous medium also agrees well with the experimental data. The expression can be applied successfully to design porous castings for filtering and noise reduction.

Based on the graph, the rate of permeability was the highest when the porosity was at 71.01%. The theory followed by the least permeable at the lowest porosity. Besides that, the result for experiment and numerical quite different in value. This is because of the different kind of characteristic that aluminium foam possesses compared to soil.
3.5. Pore Structure

For every sample of the aluminium foam tested, each has different pore structure level. These particular characteristics is very essential in determining the value of heat conductivity of aluminium foam. Clearer view of the pore structure of the aluminium foam is scanned by using the scanning electron microscope (SEM) TM3000 tabletop microscope machine. Each of the aluminium samples is scanned and magnified images of each samples are shown on the computer unit connected to the SEM.

![Figure 9. Poros structure of aluminium foam tube fabricated.](image)

From the images obtained from SEM, it can be seen that there were some white fragments in the aluminium foam. This is because of the NaCl that are not fully removed. There is still certain method that need to be discovered to remove the NaCl completely from the fabricated aluminium foam. If the NaCl was removed completely, the structure of aluminium foam could be seen much clearly.

Most of all the sample were in range of 1.5 mm - 3 mm of their pore size. As seen in the table, the structures of the aluminium foam were different in term of pore size and shape. Image of each sample was slightly similar. From that, it is believed that the distribution of the porous structure for the entire sample was well distributed. In the image of porous structure, the pore size of sample (a) was slightly larger than the pore size of sample (b). It is shown that the percentage of porosity and density are depending on the pore size. The larger pore size will give a higher porosity percentage.

Besides that, all of the aluminium foam sample showed that the structures are interconnecting and have random shape. The sizes of the porosity depend on the NaCl used in the fabrication.

4. Conclusion

This study focused on heat conductivity and permeability of aluminium foam. From this study, it can be concluded that the objective is achieved. Aluminium foam does have better thermal conductivity compared to solid aluminium. The heat conductivity is a decreasing function of porosity, falling off very rapidly for the first few percent of porosity, and then leveling off. Other than that, permeability of aluminium foam depends on the porosity, the higher the porosity will give out the higher rate of permeability.
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