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EVALUATION of THE SHIELDING PERFORMANCE and PRESSURE DROP of VENTILATION HOLES in A MICROWAVE FURNACE

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Abstract

In this study, shielding performance and pressure drop of the honeycomb, square and circular ventilation holes in a microwave furnace, which is operated at 2450 MHz, were evaluated. The effect of hole diameter, hole to hole distance and hole depth to the shielding and pressure drop were considered as variables. A simulation model prepared on Comsol Multiphysics v.5.2a and the results compared with the theoretical equations. The pressure drop and shielding performance decreases and increases with increasing hole diameter and hole to hole distance, respectively. Increasing hole depth causes a reduction in pressure drop but it enhances the shielding performance.

Keywords: Ventilation holes, Microwave furnace, Shielding, Pressure drop.

Introduction

Microwave furnaces are used in many industries mainly for drying purposes. Unlikely to the conventional furnaces, microwave furnaces bring on volumetric heating. This causes the temperature of core of the material is getting higher than its surface and causes an internal vapour pressure difference between the core and surface [1]. Because of the pressure difference, the water migration from the material enhances and water molecules accumulate at the surface. Therefore, it is necessary to remove moisture during drying from the furnace environment with the forced air flow [2]. This allows keeping the relative humidity inside furnace and helps the extraction of moisture from the material. The air flow is generally designed as a closed loop and the amount of moisture taken from the material is condensed by passing the saturated air over a cooling battery or released to the atmosphere [3]. In response to this closed loop of the air, it is not desired that

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electromagnetic wave leaks out of the oven environment from the microwave furnace [4]. For this reason, there is a need for ventilation holes that will create minimum counter pressure to the air flow in the areas where the air flow enters and exits the furnace and at the same time can attenuates the electromagnetic field and keep it in the furnace [5]. There are many geometric shapes and calculation methodologies in the literature that serve this purpose [4-12].

Among from them, Connor and Archambeault was derived a simple equation in order to quantify the shielding performance of square ventilation holes. The shielding is determined as a function of hole size, number of holes, hole to hole distance and depth for different microwave frequencies between 3 GHz to cutoff frequency of the hole. They found that the shielding performance is in a good agreement with the experimental data. On the other hand, they implied that the shielding for whole combinations at the near region to the cutoff frequency is independent from the hole depth [4]. The leakages from large thin openings were also investigated and it was found that the shielding efficiency decreased against increasing slot dimensions [8]. Rakhsit was investigated the shielding effectiveness of the honeycomb shape for different core depth and cell width. It is noted that the pressure drop for any system should take into consideration in order to reduce the power requirements of the system. It is found that the attenuation is increased with increasing core depth per cell width [6]. However, Bereuter et al. deduced that the shielding performance of the honeycomb structure can easily change by manufacturing divergence even with a small crack considering the project [10]. Jackman et al. were studied the relationship between attenuation and pressure drop for perforated enclosure panels. They made an experimental setup in order to measure the air velocity and electromagnetic emission for different shapes and sizes of holes. They found that both the air velocity and emissions were decreased with the reduction of total opening area. They implied that the perforation pattern is very important for optimizing pressure loss and electromagnetic emissions [5]. Similarly, Otoshi was investigated microwave leakages from the circular shaped perforated plates with staggered and square array of holes. He represented a quick formula for estimating the transmission losses and validated with experimental study. He found that the formula matches with the experimental data in ±1 dB for S band frequencies when the transmission losses are greater than 20 dB. He also implied that the array configuration doesn’t affect the shielding efficiency [7]. Archambeault pointed out that the price of air ventilation shield and effectiveness is getting higher when the hole size is getting smaller [9].

In the aforementioned studies, the relationship between pressure losses and attenuation due to the shielding structure is conceptually well defined, but nearly none of them quantified the pressure losses. In this study, square, honeycomb and

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circular shaped ventilation holes, which are the most preferred geometrical shapes, have been investigated for electromagnetic attenuation and pressure loss under the most used drying frequency for 2450 MHz. For this purpose, the change of a hole size, hole to hole distance and hole depth were selected as a shielding structural variable parameter. The parametric study was done by using Comsol Multiphysics v.5.2a. The aim of this work to help to the engineers on this field at the design stage.

Material and Method

The air ventilation model considered is represented in Figure 1. The square, circular and honeycomb shields were located in a 200 (mm) x 200 (mm) ventilation duct opening as described in [4]. Different than [4], the number of ventilation holes is arranged by considering the maximum number of holes depending on the hole size, in order to reduce the pressure loss.

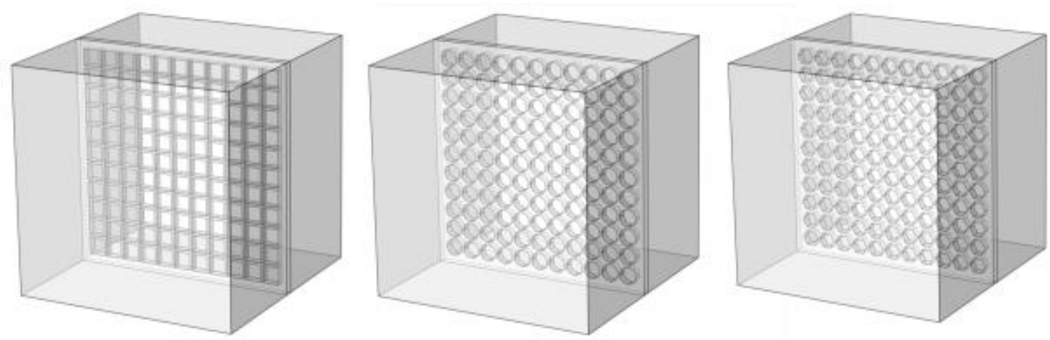

Figure 1. Simulation Models for Different Geometrical Shapes.

For the investigation the hole size, hole to hole distance and hole depth of the shield is determined by considering the working frequency's wavelength of the furnace. The wavelength of the frequency is found by Equation 1. In this study, the dimensions corresponding to the $\lambda_0/12$, $\lambda_0/24$, $\lambda_0/36$, $\lambda_0/60$ and $\lambda_0/124$ were selected. The number of holes in the horizontal and vertical directions are determined by locating maximum number of holes regarding to the hole size and hole to hole distance. The simulations were conducted for whole combinations of the parameters given in Table 1. Also, the mesh independency study were done for computational fluid dynamics (CFD) analysis by changing the mesh quality by using default selections on the program as extremely coarse, normal, fine and extremely fine. In order to supply the required resolution in time and frequency domain, the electromagnetic model mesh structure is selected as extremely fine.

$$\lambda_0 = \frac{c}{f} \quad (1)$$

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Here, λ_0 is wavelength of given frequency (m), c is the speed of light ($3x10^{-8}$ (m/s)) and f is the frequency (Hz).

Table 1. Simulation Input Parameters.

Parameter	Value
Hole Size "d" (mm)	10.20, 5.10, 3.40
Hole Depth "t" (mm)	10.20, 5.10, 3.40, 2.04, 0.99
Hole to Hole Distance "l"(mm)	3.40, 2.04, 0.99
Frequency (MHz)	2450

For the electromagnetic and CFD analyses, the simulations were done under frequency domain and stationary study, respectively. The boundary condition locations on the proposed model are given in Figure 2.

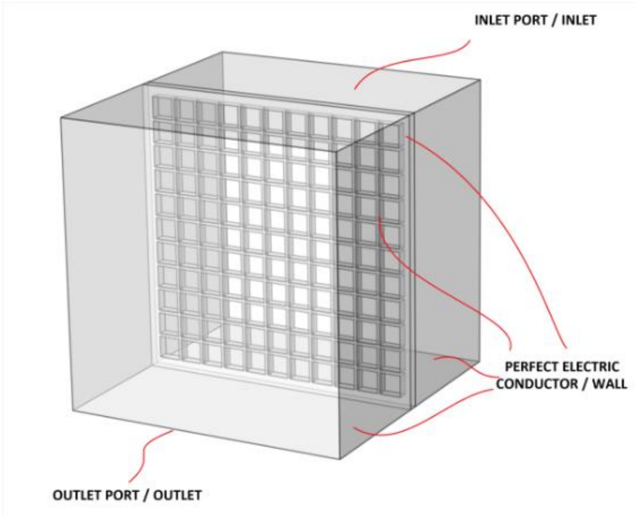

Figure 2. Boundary Conditions for Electromagnetic and CFD Analyses.

The inlet and outlet port are selected as rectangular port and the mode type is selected as transverse electric 10 mode which is the dominant mode for standard waveguide of 2450 MHz [3]. The inlet and outlet port were located one wavelength distance from the shield as in [4]. The attenuation is power independent at given frequency [13]. In this way, the inlet port excitation power is considered as 1 (W) for the electromagnetic analyses. The attenuation due to the metallic duct losses is very low and negligible due to high conductivity values of the metals [3]. For this reason, the perfect electric conductor boundary condition was applied to the walls of the duct and holes. In the CFD analyses, inlet air velocity and outlet pressure of the duct was considered as fully developed with 10 (m/s) and 0 (Pa) regarding to the optimum working conditions of atmospheric industrial furnace requirements [14]. In order to validate the simulation model, a validation study is done for the parameters given in Table 2 [4].

Table 2. Validation Study Parameters.

Parameter	Value
Air Ventilation Width (mm)	91
Air Ventilation Height (mm)	31
Hole Size “d” (mm)	9
Hole Depth “t” (mm)	7
Hole to Hole Distance “l”(mm)	1
Total Holes in Horizontal Direction	9
Total Holes in Vertical Direction	3

To compare shielding effectiveness “SE_{db}”, and pressure drop “ΔP” found in this study, theoretical equations given for different geometrical shapes which are represented in Table 3 were used.

Table 3. Theoretical Shielding Formulas for Different Geometrical Shapes

Shield Shape	Equation No	Equation	Reference
Square	3	$SE_{dB} = 56 - 3.5d - 20\log_{10}(\frac{f}{1000}) + 25\frac{(t-1)}{d}; \text{for } f \leq \frac{f_{ch}}{3}$ $SE_{dB} = \left[56 - 3.5d - 20\log_{10}\frac{(\frac{f_{ch}}{1000})}{3} + 25\frac{(t-1)}{d}\right]\left[1.5\left(1 - \frac{f}{f_{ch}}\right)\right]^{\frac{2}{3}}; \text{for } \frac{f_{ch}}{3} < f < f_{ch}$	[4]
Square	4	$SE_{dB} = 27{,}3\frac{t}{d}\sqrt{1 - \left(\frac{df}{150000}\right)^2}$	[12]
Circular	5	$SE_{dB} = 20\log_{10}\left(\frac{3(l+d)^2\lambda_0}{2\pi d^3\cos\theta}\right) + \frac{32t}{d}; \text{for } d < (l+d) \ll \lambda_0$	[7]
Circular	6	$SE_{dB} = 31{,}95\frac{t}{d}\sqrt{1 - \left(\frac{df}{175800}\right)^2}$	[12]
Honeycomb	7	$SE_{dB} = 27{,}3\frac{t}{d} - 20\log_{10}\frac{2\lambda_0 d}{\pi}\cos\theta$	[4]
Honeycomb	8	$SE_{dB} = 17{,}5\frac{t}{d}\sqrt{1 - \left(\frac{df}{96659}\right)^2} - 20\log_{10}\frac{2\left(\frac{2\pi}{\lambda_0}\right)d}{\pi}\cos\theta - 20\log_{10}\frac{2\frac{d}{3{,}18}d}{\frac{f}{1000}}; \text{ for } \frac{f_{ch}}{f} > 5\frac{d}{3{,}18}$ $SE_{dB} = 17{,}5\frac{t}{d}\sqrt{1 - \left(\frac{df}{96659}\right)^2} - 20\log_{10}\frac{2\left(\frac{2\pi}{\lambda_0}\right)d}{\pi}\cos\theta; \text{ for } \frac{f_{ch}}{f} < 5\frac{d}{3{,}18}$	[10]
Square Circular Honeycomb	9	$d_h = 4\frac{A_w}{P}$ $\varphi = \frac{A_w}{A}$ $\alpha = 0.6 + 0.4\varphi^2$ $\zeta = \left(\frac{1}{\alpha} - 1\right)^2 + (1-\varphi)^2; \text{for } \frac{t}{d_h} \gg 0$ $U_h = \frac{U}{\varphi}$ $\Delta P = \frac{1}{2}\rho {U_h}^2$	[15]

For the equations, d is the hole size (mm), f is the frequency (MHz), t is the hole depth (mm), f_{ch} is the cutoff frequency of the hole size (MHz) which is calculated by Equation 2, λ_0 is the wavelength of operating frequency (mm), l is the hole to hole distance (mm), θ is the angle of incident wave (°), d_h is the hydraulic diameter for a given geometrical shape (mm), A_c is the wetted area (m^2), P is the wetted perimeter (m), φ is the porosity (%), A is the cross section area of ventilation hole

(m^2), α is the discharge coefficient, ζ is the pressure loss coefficient, U is the bulk velocity of the air (m/s), U_h is the air velocity inside the holes (m/s) and ρ is the air density (kg/m^3).

$$f_{ch} = \frac{\frac{c}{2\frac{d}{1000}}}{1000000} \quad (2)$$

Results and Discussion

Validation of the Model and Mesh Independency

Validation of the model was done by comparing the simulation results with the experimental data obtained from the literature [4]. The mesh quality of the electromagnetic analyses was selected as extremely fine on the program and the results are given in Figure 3. As one can see from the figure, the simulation model was represented very good match with the experimental data.

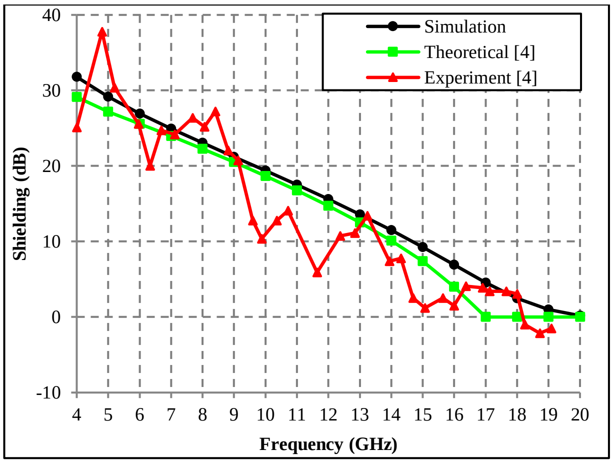

Figure 3. Validation of the Electromagnetic Analyses

The honeycomb structure has the most complicated geometrical structure for the proposed geometrical shapes considered in this study. Thus, the mesh independency study was conducted for the honeycomb structure and the results were compared with the theoretical formula which is represented in [15]. The evaluation of the pressure drop for different kind of default meshes for d: 5.10 mm and l: 3.40 mm were demonstrated in Figure 4. As one can see from the figure, the relative error of pressure drop between theoretical and simulation results were decreases when the mesh quality is increasing and the hole-to-hole distance is decreasing. The maximum error realized from the mesh independency study is ±%12.20.

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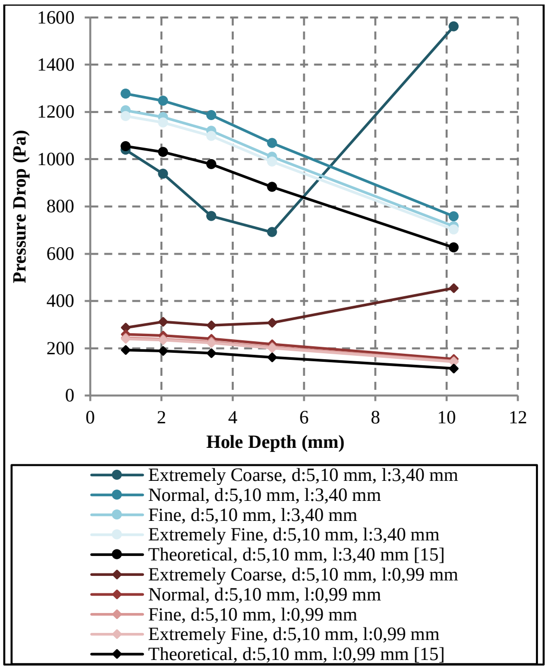

Figure 4. Mesh Independency Results for CFD Analyses

Shielding Performance

Shielding performance of a given various geometrical shapes as a function of hole diameter, hole to hole distance and hole depth under constant 2450 MHz is given in Figure 5. According to the wave theory, scattering of the wave between the walls of the structure and thus the attenuation depends on the wall structure type. The rate of reflection inside ventilation hole determines the attenuation. Because of geometrical complexity of the honeycomb shape which allows reflection inside the structure, it showed better shielding performance to others. However, the difference between honeycomb and circular shaped hole is nearly negligible. One can be said that, due to the manufacturing costs, the circular shape has advantage than the honeycomb, thus the circular shape could be chosen. On the other hand, the difference between the different geometrical shapes is more apparent when the hole depth is increased. At low thicknesses, the effect of the geometrical shape is not important. The shielding performance linearly improves when depth value is getting higher. Also, when the hole size decreases the rate of change shielding performance is getting higher. The porosity of the ventilation holes which is dependent on the hole size and hole to hole distance also effects on the shielding performance. The square shape has the most porous structure, thus the change of hole to hole distance has significant effect on shielding performance for that kind of shape. As depicted on the figure, the shielding performance decreases when the porosity increases. The figure also shows the consistency of the theoretical shielding performance for the

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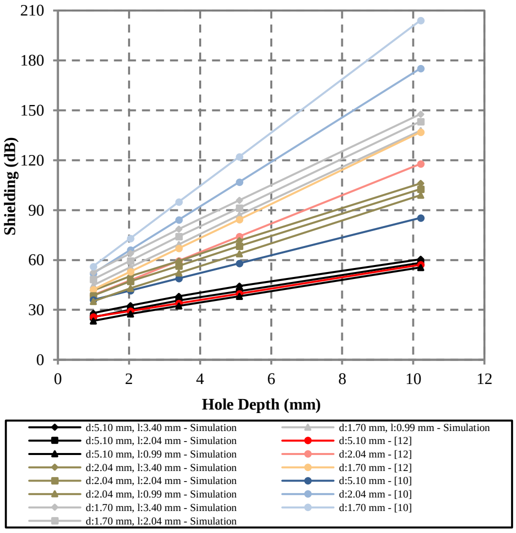
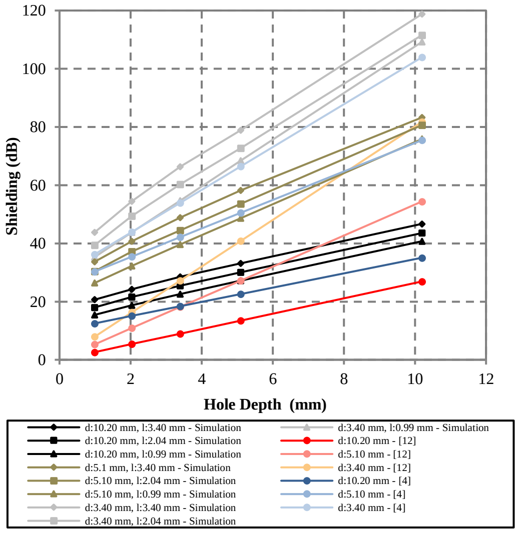
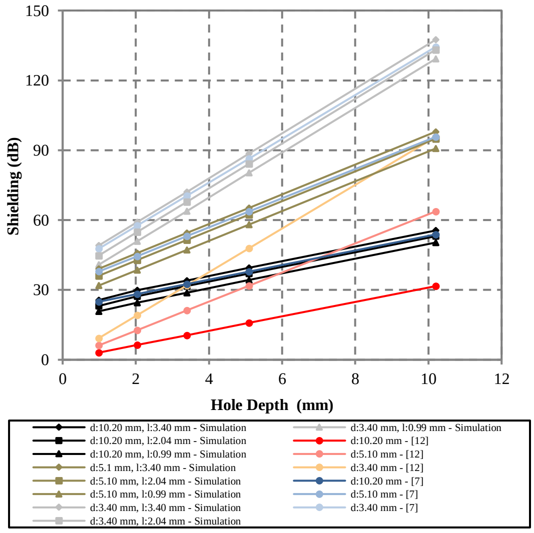
geometrical shapes. It is found that the theoretical formulas don't represent the actual shielding performance due to the lack of hole to hole distance term inside the formulas. From the figure, it is understood that the formulas has the best matching characteristics when the hole diameter is getting smaller.



(a)



(b)



(c)

Figure 5. Shielding Performance of (a) Honeycomb, (b) Square and (c) Circle shapes.

However, they have ability to show the increasing or decreasing trend of the shielding. Formulas gathered from [12] used for all geometrical shapes considered in this study but it gets the most appropriate results for honeycomb shape. It hasn't showed realistic results for square and circular shape. The best concordance is realized for square and circular shapes when the equations 3 and 5 are used,

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respectively. The high transmission losses are identified where the losses are greater than 27 dB [11]. Considering this value, the square shape can be used when the hole depth equal or greater than 5.10 mm when the hole diameter equals 10.20 mm and regardless from the hole to hole distance. For the circular and honeycomb shape, the critical depth value is 2.04 mm.

Pressure Drop

Pressure drop of a given various geometrical shapes as a function of hole diameter, hole to hole distance and hole depth under constant velocity as 10 m/s is given in Figure 6.

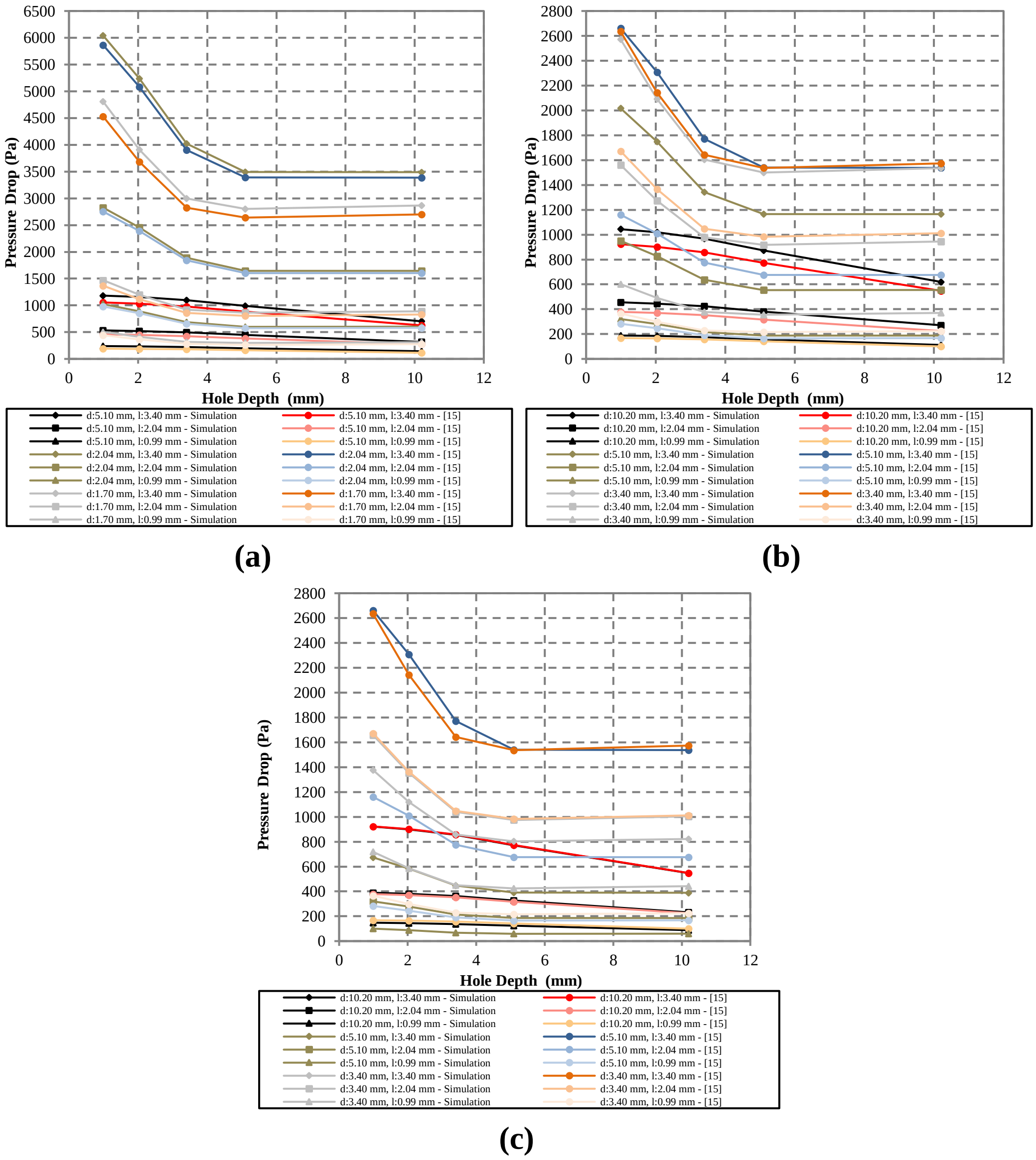

Figure 6. Pressure Drop of (a) Honeycomb, (b) Square and (c) Circle shapes.

As expected, the pressure drop increases with increasing hole to hole distance and decreasing hole diameter. This causes a less porosity on the structure and the counter pressure increases against the flow direction thus the pressure drop increases. It is interesting to note that the curve linearity is changed when the hole diameter equals to 3.40 mm. At this value, all of the geometrical shapes have exponential curves. Also, when the hole depth is getting smaller, the pressure drop of the ventilation hole increases. The advantage of geometrical complexity is not valid also for pressure drop. The figure showed that pressure drop increases with geometrical complexity. In this context, the smallest pressure drop values were obtained for circular shaped structures. Also it can be said that the more edges for the geometrical shape, the more pressure drop would occurred. The fan power increases with the pressure drop at the same flow rate. Thus the low pressure drop allows selection of the smaller fan. For this reason thicker ventilation hole should be desired at the design stage. Different from the shielding performance, the theoretical pressure drop equation gathered from [15] showed good matching for all geometrical shapes. The equation nearly showed the same value obtained from the simulations for circular shape. As a result, the formula could be used freely at the design stage of the project.

Conclusion

In this study, the pressure drop and shielding performance of the various geometrical shapes for a ventilation holes in a microwave furnace which is operated at 2450 MHz was investigated. Electromagnetic and CFD analyses were done in order to compare the relationship between shielding and pressure drop. The main findings of this study can be summarized as follows:

- Pressure drop and shielding increases with increasing hole to hole distance.
- The pressure drop and shielding performance decreases with increasing hole diameter.
- Pressure drop decreases with increasing hole depth, however the shielding performance increases.
- The circular and honeycomb shapes show better shielding performance than square shaped ventilation holes. However, the circular shaped ventilation hole has the smallest pressure drop, thus it required less fan power and manufacturing costs. As a result, the circular shape is the most advantageous geometrical shape.
- The theoretical equations gathered from the literature for determining the shielding performance did not represent the simulated values. However, the equation for pressure drop showed good agreement with simulated data.

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In further studies, the effect of sharp and round entrance of the geometrical shapes on the shielding performance and pressure drop characteristics should be considered. Also, the manufacturing and fan costs should be analyzed.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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