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Metal Casting Furnace Design Development Using Computer Simulation

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ABSTRACT

Metal foundries still rely heavily on crucible furnaces. The current furnace design, which is currently being used by the partner industry, has been found to be not properly designed and will result in a reduction in efficiency. CFD simulation will be used to find the optimal melting furnace design. This research simulation consists of 3 stages: pre-processing, solving, and post-processing. There are two furnace geometries, cylindrical and hexagonal, while the burner location will be divided into 3 positions, namely P1, P2, and P3. The most optimal furnace design will be used as a basis for the verification testing process. The process of comparing the old and the new smelting furnace design is carried out to understand the performance and characteristics of each furnace. The simulation results for the average crucible temperature in the cylindrical furnace were obtained as follows: 288.5 ºC for the P1 burner, 306.2 ºC for the P2 burner, and 284.5 ºC for the P3 burner. Meanwhile, the simulation results show that the average crucible temperature value in the hexagonal furnace is 290.0 ºC for the P1 burner, 281.6 ºC for the P2 burner, and 237.8 ºC for the P3 burner. The verification testing process produced an average crucible temperature value of 237.5 ºC. Furthermore, the comparison test from the old and new furnace designs to melt 2.5 kg of aluminium at 680 ºC with the old furnace took approximately 30 minutes and 33 minutes with the new furnace. The new furnace produced much more uniform melting than the old furnace.

Keywords: *Computer simulation, crucible furnace, design development, metal casting*

I. Introduction

The current condition of the manufacturing industry in Indonesia still relies heavily on previous technology, especially the metal forming process. The development of science and technology has given rise to various modern equipment that can increase productivity [1]. However, the emergence of modern equipment has not been able to replace previous technology in the metal forming process, one of which is the metal casting method.

The metal casting process is a product formation technique by melting metal in a melting furnace and then pouring the molten metal into the mould cavity [2]. The types of furnaces most commonly used to melt the metal are crucible, electric arc, and induction furnaces [3]. The selection of the furnace type depends on factors such as melting temperatures, capacity requirements of the stove, costs, and environmental pollution considerations [4].

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The type of metal casting that is widely used is sand mould because it has economical production costs and is able to make castings with magnitude up to the ton scale [5]. However, foundries spend about 5-10% on average of their total revenue fixing internal and external deficiencies due to the sand casting process [6]. Mr. Endik's metal casting industry, located in Pasuruan City, is an example of a foundry industry that applies a type of metal casting using sand moulds. Mr. Endik ran the furnace using an LPG as a fuel and didn’t use a blower for the setup, although the common combustion method involves mixing the fuel LPG gas and air from the blower [7]. For the most part, Mr. Endik only focuses on aluminium metal casting. The choice of aluminium metal was due to the limitations of the melting furnace used, which gave the impression that it had not been designed well previously. This causes low peak furnace temperatures and wasteful use of fuel. The uneconomical use of fuel will increase production costs, so it is essential to change the design of the melting furnace to be more efficient by considering the existing design parameters.

One of the steps to start designing a melting furnace is to use numerical methods. The existence of this numerical method makes it possible to simulate melting furnaces to find the most efficient design before implementing it directly in the real world. Numerical simulation is considered very beneficial because it provides some important information that can help improve several aspects of actual operations [8]. Computational Fluid Dynamics (CFD) simulation will be used because of its ability to obtain test parameters without having to carry out actual testing [9]. CFD is a good tool for getting detailed information about heat transfer, fluid flow, and combustion characteristics inside a furnace [10].

The melting furnace design that will be varied is the location of the burner and the geometry of the furnace. Furnace geometry is divided into two types, namely cylindrical furnace designs according to those used in partner industries and induction furnace designs with hexagonal geometry according to the reference [9]. The hexagonal furnace geometry will be applied to gas-fired casting furnaces and compared with the current cylindrical geometry. So, these two proposed furnace designs, cylindrical and hexagonal-shaped furnace designs, are different in geometry and shape but have similar sizes. The two proposed furnaces are evaluated using computer simulation to compare their performance. This paper focused on the various efforts made to improve the performance of the poorly-designed and impractical old furnace with the two proposed furnace designs, especially as they are developing in the small industry, which gave the impression of their small amounts of resources and financial situation. Therefore, this paper aims to assist the partner’s industry in developing the new furnace design as well as replacing the poorly-designed furnace as they struggle to make a new one or reconstruct it by simulating several smelting furnace designs to find the most optimal design and compare the simulation results with the results obtained through experimental testing, and also carrying out the comparison testing between the old and the new furnace to understand the performance and characteristic.

II. Material and Methods

Material selection is crucial in developing furnaces [11] because furnaces operate in an aggressive environment where components of molten metal, atmospheric gases, furnace lining, and combustion products from fuel coexist at extremely high temperatures [12]. Therefore, materials that can be used to fabricate gas-fired crucible furnaces are engineering materials with good thermal, electrical, and mechanical properties [13].

Generally, gas-fired crucible furnaces can be categorized into four types: furnace casing, insulation, crucible pot, and accessory [14]. Selecting appropriate materials is expected to enhance furnace performance and its service life. In this study, the materials used for simulation are cast iron, steel, refractory lining (insulation), and aluminium. Both steel and aluminium materials are already available in the ANSYS material database along with their properties. However, the cast-iron and refractory lining properties are obtained based on references [15],[16]. Properties of materials used for simulation are shown in Table 1.

Table 1. Material Properties of Different Materials

Material Name	Density	C_p	Thermal Conductivity
	$[\mathrm{kg/m^3}]$	$[\mathrm{J/kg \cdot K}]$	$[\mathrm{W/m \cdot K}]$
Steel	8030	502.48	16.27
Aluminium	2719	871	202.4
Cast-iron	7230	506	26.1
Refractory lining	2100	1550	1.0007

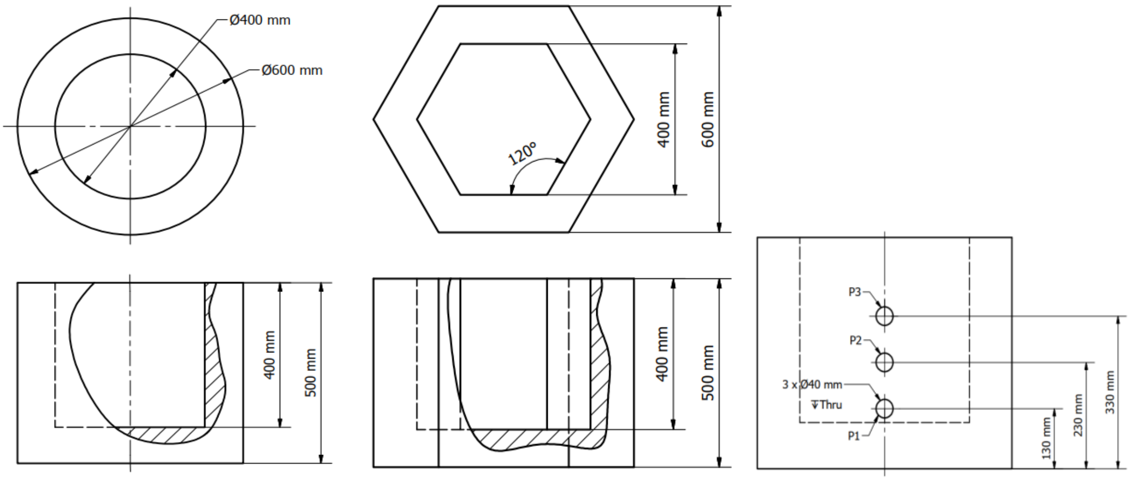
The research methods are divided into two: computational analysis methods through CFD simulations and experimental approaches by directly testing furnaces in partner industries.

1. Computational

The development of the melting furnace design was carried out using CFD simulation via ANSYS 2020 R2 software. The stages in developing a melting furnace design using ANSYS software are as follows.

1) Pre-processing is the initial stage in building and analyzing computational models. The pre-processing steps mainly carried out in this study are modeling, meshing, and boundary conditions parameters.

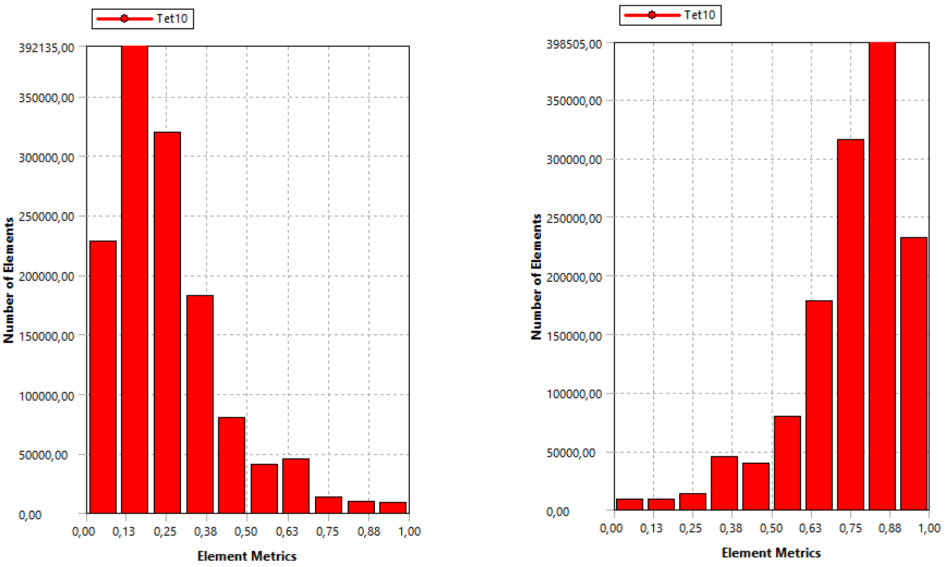
   Figure 1 represents the details for the geometry dimension of the two proposed furnace designs shown in Figure 1 (a) and Figure 1 (b). Meanwhile, the burner positions are located in three different locations, as shown in Figure 1 (c).



(a) (b) (c)

Fig. 1. (a) Cylindrical furnace geometry, (b) Hexagonal furnace geometry, (c) Variations in burner location

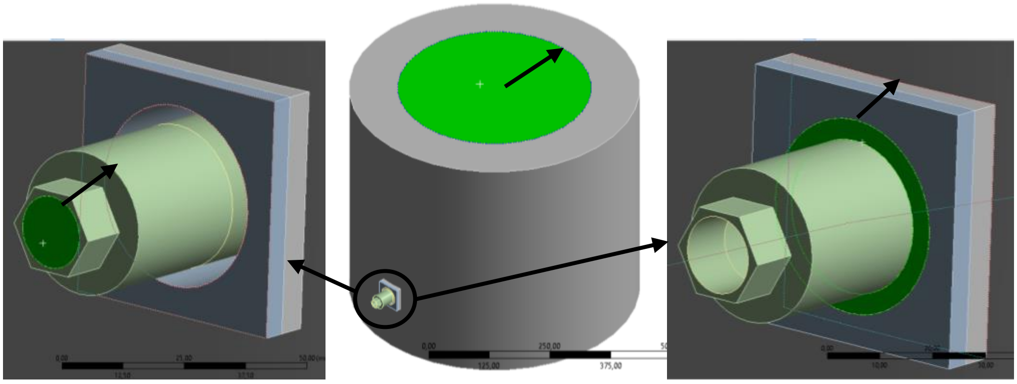
This simulation of research consists of several meshing methods. The meshing type is set to the default. The element size of both the furnace and air are set to be at 10 mm. The crucible, aluminum, and burner, all of them are using a combination of edge sizing (using a number of divisions type) and face meshing. This setup gave much less computing time while maintaining the meshing quality. The meshing skewness averages 0.24769, while the orthogonal quality averages 0.75086. The distributions of skewness value and orthogonal quality of each element node can be seen in Figure 2.



(a) (b)

Fig. 2. The Mesh element metrics: (a) Mesh skewness, (b) Mesh orthogonal quality

In this simulation, a mixture of 30% propane (C_3H_8) and 70% butane (C_4H_{10}), also known as petroleum gas, was used as the oxidizer for combustion. The fuel inlet was modeled as a mass-flow inlet. On the other hand, atmospheric air was forced at a constant velocity (see Table 2) into different inlets (air inlet), whereas the outlet is fully opened without a furnace lid. The boundary conditions for the fuel inlet, air inlet, and outlet can be seen in Figure 3.



(a) (b) (c)

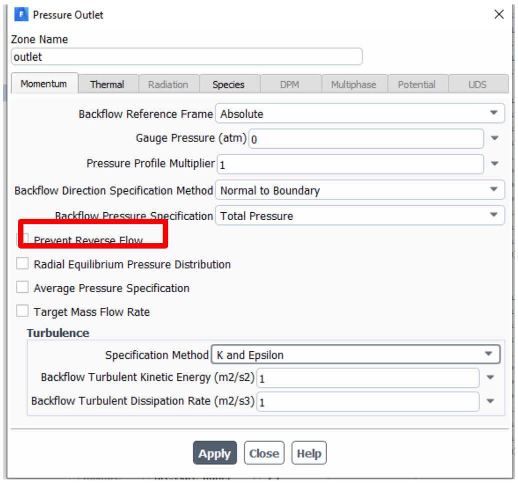
Fig. 3. Boundary Conditions: (a) Fuel inlet, (b) Outlet, (c) Air inlet

The parameter input for the fuel inlet and the air inlet are shown in Table 2.

Table 2. Parameters input and values

Boundary Name	Parameters	Value
Fuel inlet	Mass-flow Rate (kg/s)	0.00083
	Temperature (K)	300
	Initial guage pressure (atm)	2
Air inlet	Velocity magnitude (m/s)	10
	Temperature (K)	350
	Initial gauge pressure (atm)	0

The outlet parameter was performed by activating the prevent reverse flow, as shown in Figure 4.



Zone Name: outlet

Backflow Reference Frame: Absolute
Gauge Pressure (atm): 0
Pressure Profile Multiplier: 1
Backflow Direction Specification Method: Normal to Boundary
Backflow Pressure Specification: Total Pressure
☐ Prevent Reverse Flow
☐ Radial Equilibrium Pressure Distribution
☐ Average Pressure Specification
☐ Target Mass Flow Rate

Turbulence
Specification Method: K and Epsilon
Backflow Turbulent Kinetic Energy (m2/s2): 1
Backflow Turbulent Dissipation Rate (m2/s3): 1

Fig. 4. The outlet parameter conditions

2) Solving is a processing stage where the conditions that have been set during pre-processing in the CFD software will be calculated.
3) Post-processing is the final stage in the CFD simulation, which will display the data from the CFD simulation results. The post-processing stage in this study will carry out the average temperature of the crucible, the temperature contour, and the streamlining of the fluid inside the furnace.

2. *Experimental*

The testing process at this stage begins with fabricating a melting furnace according to the best simulation design results. The procedures for constructing a furnace were as follows: (1) Preparing the tools and materials, (2) Assembling the burner pipe, (3) Building the furnace, (4) Assembling components, (5) Furnace testing, (6) Finish.

After the furnace has been constructed, the next step is to carry out a verification test of the simulation results, where in this verification test, the average crucible temperature value from the simulation test results will be compared with the newly constructed furnace. This verification testing is carried out to verify and proven the simulation's convergence. The average crucible temperature results from a simulation method are expected to be higher than the experimental one. This is because in the computational simulation, there are several parameters that are in an ideal condition, which was hard to achieve in reality. For example, the parameters input such as the fuel supply. In the simulation, the fuel supply will be the same throughout the entire simulation process, while in the real world, such condition is harder to duplicate. Another example is the properties of the material which is vary as the temperature rises, while the simulation's material properties value is determined to be constant.

A comparison test is performed to both the old furnace and the new furnace by melting 2.5 kg of aluminium to understand the performance and characteristics of the old furnace used by partner industry and the new furnace designed according to the simulation results. This testing is performed by calculating how long for the aluminium until it's reached the melting temperature of 680 ºC. The measuring instruments that are being used to perform this comparison test are thermometer and thermocouple type-K to measure the aluminium temperature and a stopwatch to measure the time spent during the test carried out of each furnace.

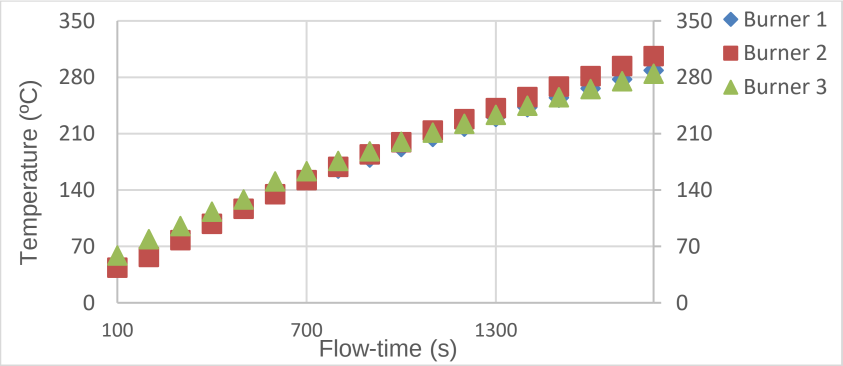
III. Result and Discussion

The simulation results obtained in the form of average crucible temperature values are presented in Table 3.

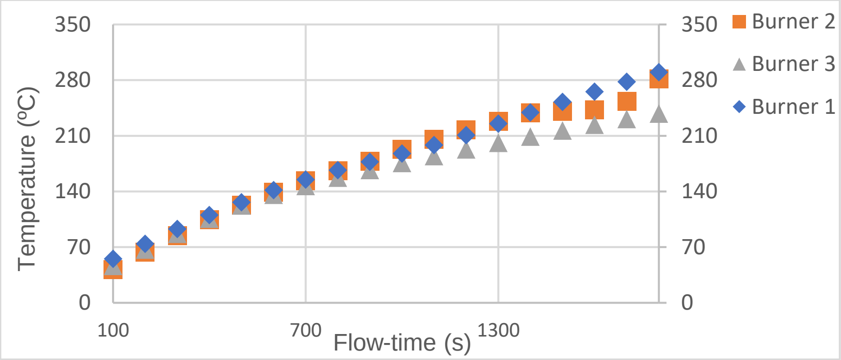
Table 3. Smelting furnace simulation results

No	Furnace	Burner locations	Average temperature of crucible [ºC]
1	Cylindrical	P1	288.5
2	Cylindrical	P2	306.2
3	Cylindrical	P3	284.5
4	Hexagonal	P1	290.0
5	Hexagonal	P2	281.6
6	Hexagonal	P3	237.8

Figure 5 is a graph of the distribution of average crucible temperature and melting time in the furnace which shows changes in crucible temperature as melting time progresses. The trend in Figure 5(a) and 5(b) shows that the average crucible temperature tends to increase steadily. Data collection for the average temperature value of the crucible was obtained using a frequency of 100 seconds, while the simulation time used in this research was 1800 seconds. The highest average crucible temperature in the cylindrical furnace geometry was obtained using the P2 burner position design, namely 306.2 ºC. The P1 burner position produced a crucible temperature of 288.5 ºC, while the lowest crucible temperature value of 284.5 ºC was obtained using the burner P3. Then, the highest average crucible temperature was obtained in the hexagonal furnace using the P1 burner position design, namely 290.0 ºC. The P2 burner position produced a crucible temperature of 281.6 ºC, while the lowest crucible temperature value of 237.8 ºC was obtained using burner position P3.



(a)



(b)

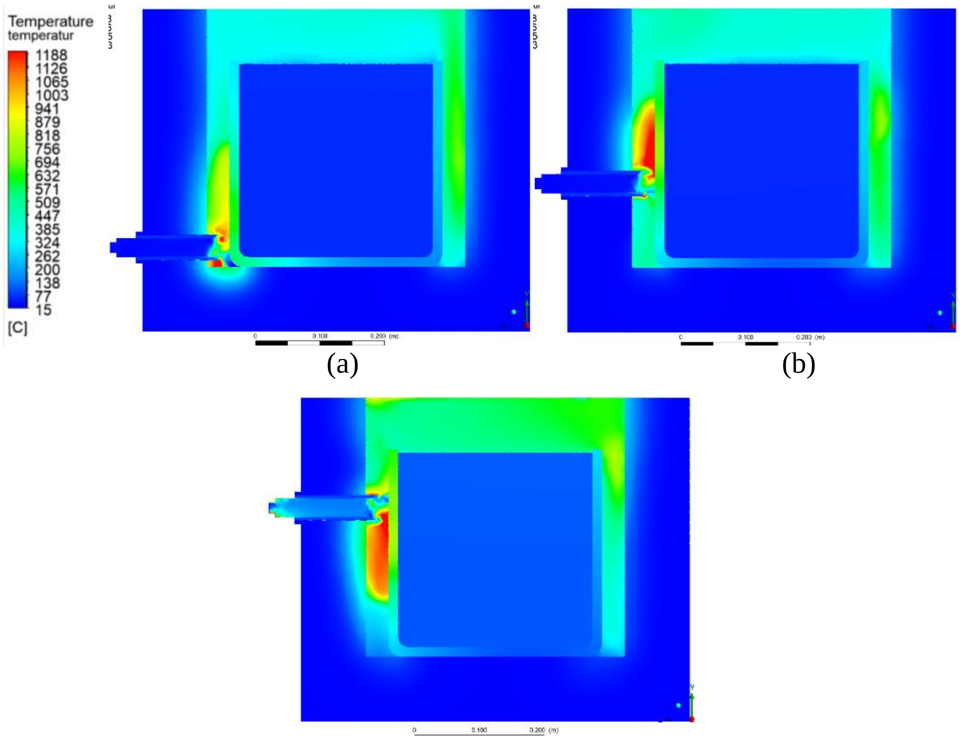
Fig. 5. Graph of average crucible temperature increase against melting time; (a) Cylindrical furnace, (b) Hexagonal furnace

1. *Simulation Results on the Temperature Field*

Furnaces with cylindrical geometry tend to have good heat distribution compared to hexagonal geometry, where on the back side of the crucible in the melting furnace, there is an area with relatively high-temperature contours at the three positions of burner P1, burner P2, and burner P3 as shown in Figure 6. This indicates that the heat flow can be well-channeled and cover the crucible.

The cylindrical geometry had a principle close to spiral turbine housing. The spiral turbine housing was designed with due considerations to ensure compatibility with decreasing the hydraulic loss and keeping the constant flow at an angle [17]. The housing shape was designed with a cylindrical and spiral geometry. Now let’s imagining that the spiral housing wall was the furnace wall and the guide vanes were the crucible. The hexagonal housing will cause much more turbulence, and the water stream will lose its energy before it hits the vanes. Comparing that with the perfectly smooth spiral wall (cylindrical shape), the water will flow more smoothly, allowing the vanes harvesting the energy of the water. That phenomenon is exactly what happened with the principle of a gas flow inside the furnace. The cylindrical furnace's gas flow circulated around the crucible more efficiently.

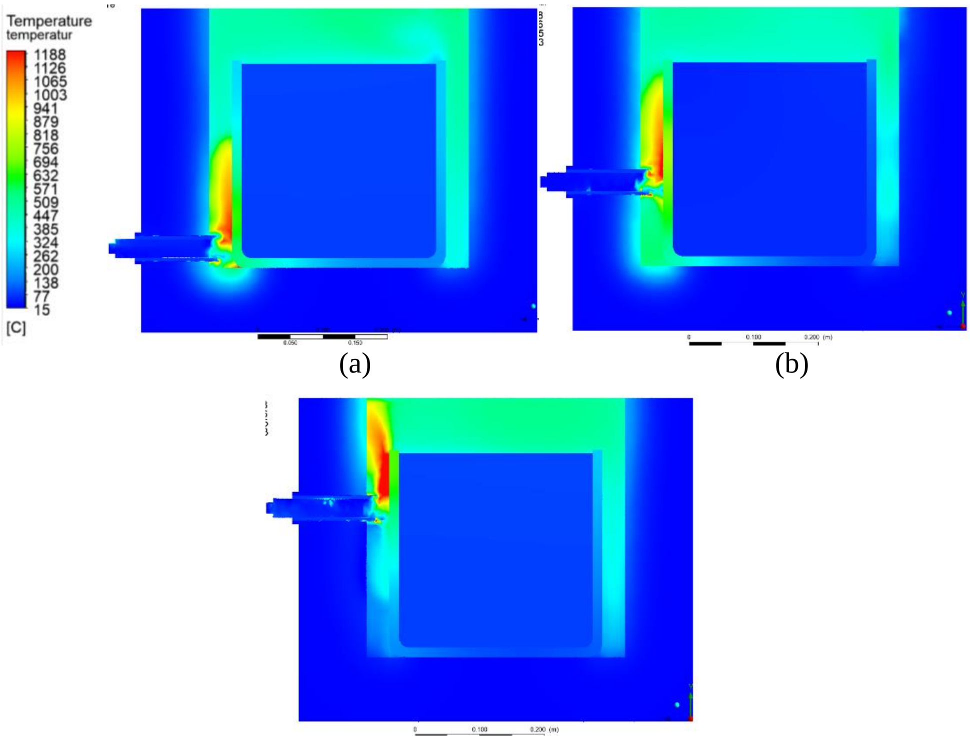
The furnace with burner position P1 produces the highest average temperature value of all hexagonal furnace variants, namely 290.0 ºC. This design with the P1 burner position produces a crucible temperature contour that tends to be even; this is proven by Figure 7(a), where, based on this image, the crucible in the melting furnace has an even distribution at the bottom, top, and behind.



(a) (b)

(c)

Fig. 6. Temperature field on the center plane form the side view (x=0) of the cylindrical furnace at t=1800 s; (a) Burner P1, (b) Burner P2, (c) Burner P3



(a) (b)

(c)

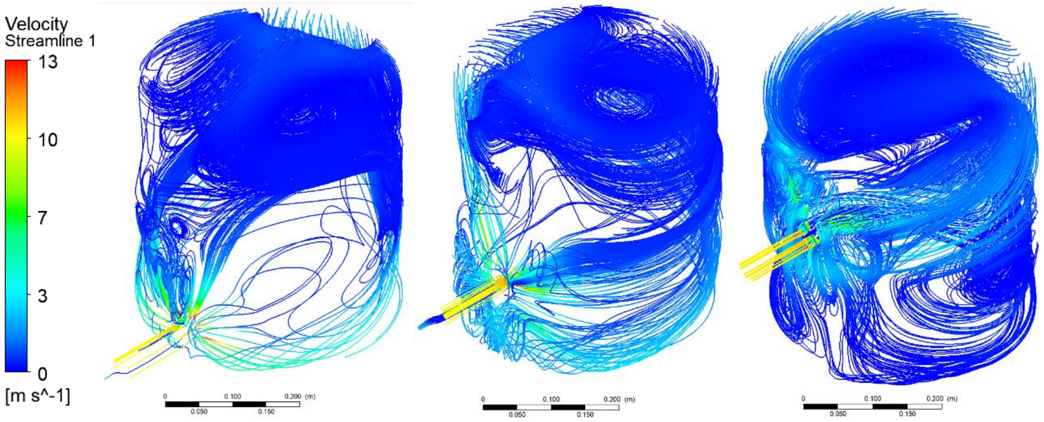
Fig. 7. Temperature field on the center plane form the side view (x=0) of the hexagonal furnace at t=1800 s; (a) Burner P1, (b) Burner P2, (c) Burner P3

In the crucible furnace, the generated heat by the gas burner is blasted by a blower; thus, it has pressure. Therefore, the blown heat that has a tangential force and will be flowing surround as it is retained by the furnace's inside wall [18]. Therefore in this particular case, the hexagonal geometry simply couldn’t retain the gas flow to be in the circular pattern like a screw line because of it’s wall shape being at an angle, thus interfering the gas flow. This phenomenon can be proven by Figure 7(b) where the hexagonal geometry furnace with the P2 burner position on the back side of the crucible tends to have a low temperature, this occurs because the heat flow cannot completely cover the surface of the back side of the crucible. This results in the area that is not exposed to heat will have a relatively low temperature.

2. *Simulation Results on Fluid Flow Characteristics*

Furthermore, the fluid flow from the burner position P1, shown in Figure 8(a), produces a relatively centralized hot fluid flow that collects in certain parts, thus causing non-uniform temperatures on the crucible walls. This causes the P1 burner position to have a lower average temperature of the crucible than the P2 burner position, namely 288.5 ºC, where there will be several sides of the crucible wall whose temperature is higher than other parts.

Based on the simulation results on a hexagonal furnace, it shows that the lower the burner position, the higher the average crucible temperature, conversely, the higher the burner position, the lower the average crucible temperature, as seen in Table 3. The P2 burner position produces the value The temperature is between burners P1 and P3, this is different from the cylindrical furnace geometry where the position of burner P2 produces the highest temperature value.

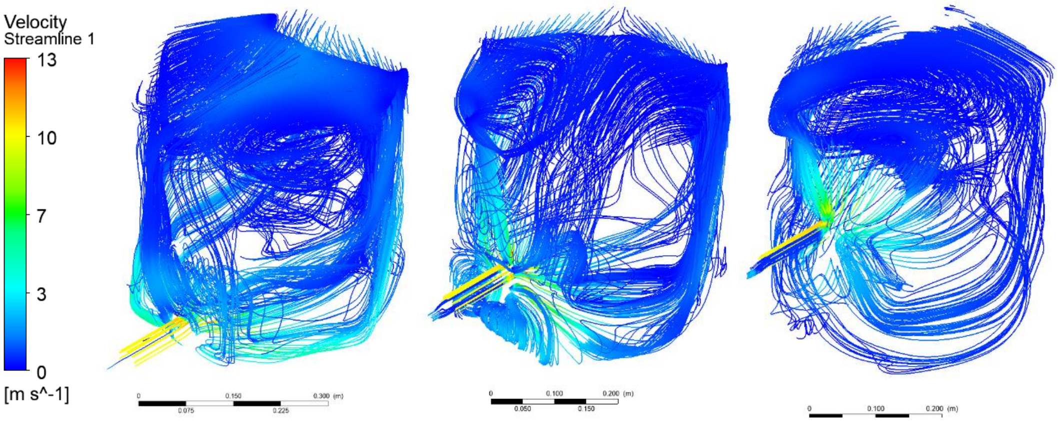


(a) (b) (c)

Fig. 8. Fluid flow scheme inside cylindrical furnace: (a) Burner P1, (b) Burner P2, (c) Burner P3

Based on Figure 9(a), the position of burner 1 produces fluid flow which tends to envelop the crucible. The same thing happens in the cylindrical furnace burner P2. This is what causes the hexagonal furnace design with burner position 1 to have higher average crucible temperature than the positions of burner P2 and P3.

The hexagonal furnace design with burner P2 produces a flow that does not envelop the back of the crucible. This is proven by Figure 9 (b), where the back side of the crucible tends not to be covered properly, which will cause the temperature on the back of the crucible to be low because the heat is not distributed properly, as proven by Figure 7(b). This phenomenon occurs because the geometry of the hexagonal furnace has 6 sides so the inner side walls of the furnace are formed at an angle that affects the heat transfer in the furnace. This is in accordance with the statement in reference [20], where if the walls of a furnace are not formed at an angle, it will help reduce the risk of forming a stagnation zone, which blocks the transfer of heat from the hot gas to the metal charge.



(a) (b) (c)

Fig. 9. Fluid flow scheme inside hexagonal furnace; (a) Burner P1, (b) Burner P2, (c) Burner P3

The salient details of the two proposed furnace designs are shown in Table 4.

Table 4. Details of each furnace configurations

Furnace Geometry	Burner Position	Caption(s)
Cylindrical	P1	- The gas charge could reach the back of the crucible wall. - The gas charge didn't cover the crucible wall evenly, resulting ununiform crucible temperature.
Cylindrical	P2	- The gas charge could reach the back of the crucible wall. - A swirl flow is formed and covered the crucible wall much evenly, resulting the highest average crucible temperature.
Cylindrical	P3	- The gas charge could reach the back of the crucible wall. - Because the burner position is so far up, the bottom part of the crucible didn't absorb the heat from the burner, resulting in a lower temperature at the bottom.
Hexagonal	P1	- The gas charge was forming a slight split stream through the right and left sides of the crucible, resulting in the highest average crucible temperature in the hexagonal geometry configuration.
Hexagonal	P2	- The gas charge formed with this geometry experienced extreme turbulence, and the flow didn't reach the back side of the crucible. Resulting in a lower average crucible temperature.
Hexagonal	P3	- The gas charge's characteristic is the same as that of the cylindrical geometry, where the temperature of the bottom part of the crucible is much lower. Resulting in a lower average crucible temperature.

3. *Verification Testing*

Experimental testing was carried out to verify the simulation furnace design by making a melting furnace according to the best simulation furnace design. Verification testing is carried out by measuring the average temperature of the crucible by taking four data collection points, namely T_1, T_2, T_3, and T_4 which can be seen in Figure 10.

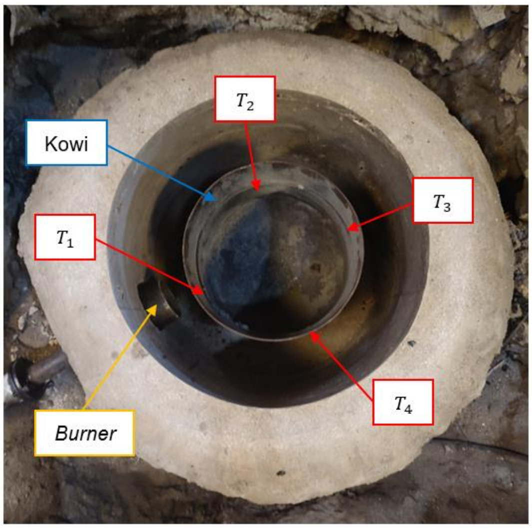


Fig. 10. Verification testing

Based on verification testing of simulation results according to the best furnace design, namely a cylindrical geometric furnace variation with burner position P2, the temperature results were T_1 = 290 °C, T_2 = 253 °C, T_3 = 217 °C, and T_4 = 190 °C, so that the average crucible temperature was equal to 237.5 °C.

4. *Testing the Old Furnaces and the New Furnace*

The old and the new furnaces are shown in Figure 11. The new furnace is located at the left-hand side of Figure 11, while the old one is at the right-hand side just beside the new furnace.

Fig. 11. Image of the new and the old furnace side-by-side

Tests of the two furnaces each used 2.5 kg of aluminium. The melting furnace is turned on and left for approximately 5 minutes for preparation. After leaving it for 5 minutes, the aluminium was put into the furnace to start the melting process. Tests were carried out to compare the performance of the old furnace with the new furnace based on simulation results. The test results of the two furnaces can be seen in Table 5.

Table 5. Test results for old furnaces and new furnaces

Furnaces	Measurement temperature [ºC]	Melting time [mins.]
Old furnace	680	30
New furnace	680	33

Based on the test results from both furnaces, the process of melting 2.5 kg of aluminium with the old furnace took 30 minutes to reach an aluminium temperature of 680 ºC, while testing on the new furnace took 33 minutes to reach an aluminium temperature of 680 ºC.

The old furnace requires a melting time of 3 minutes less than the new furnace, this is because the heat from the burner in the old furnace will directly hit the aluminium metal in the melting furnace so this can help speed up the aluminium metal melting process. This is different from the new furnace design where the heat flow from the burner is mostly used to heat the crucible placed in the melting furnace, where it will take time to heat the crucible to the melting temperature of aluminium. This is what causes the new furnace design to take 3 minutes longer to reach an aluminium temperature of 680 ºC compared to the old furnace.

However, after observing the aluminium in the smelting furnace, the new furnace produced more evenly-melting characteristics where in 33 minutes the aluminium in the crucible had completely melted. Meanwhile, testing on the old furnace after 30 minutes showed that there was still some aluminium that had not completely melted yet, especially the aluminium at the bottom that is being the furthest away from the heat source. That being said, the new furnace design produces more evenly-melting characteristics than the old one.

IV. Conclusions

After the simulation testing, the efficiency of the furnaces with cylindrical geometry is greater than that of the hexagonal shapes. This is proven by each best to the worst of its configurations. The best to worse for the cylindrical geometry was 306.2 ºC, 288.5 ºC, and 284.5 ºC, while the hexagonal best to worse was 290.0 ºC, 281.6 ºC, and 237.8 ºC. The cylindrical geometry furnace with burner position P2 produces the highest average crucible temperature, 306.2 ºC. The cylindrical furnace design with burner position P2 had a heat flow that well-covered the surface of the crucible, resulting in a uniform temperature distribution across the crucible wall. The transfer of heat from warm gas to a metal charge is hindered by the formation of stagnation zones in hexagon furnaces. This means the gas charge is undergoing much more turbulence than the cylindrical geometry. The verification test of the new furnaces in the partner industry produces an average crucible temperature of 237.5 ºC. Comparative test between the old furnace and the new furnace derived in the melting time for 2.5 kg of aluminium being 30 minutes and 33 minutes respectively to reach the melting temperature of 680 ºC. Although the new furnace took 3 minutes longer to reach a melting point of 680 ºC than the old one, the new furnace produced a better melting characteristic than the old furnace.

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