CFD COMPARISON OF IMMERSED HEATER AND OPEN FIRE BURNER DESIGNS FOR CASTING FURNACES

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ABSTRACT

In essence, only a small fraction of the heat supplied to the conventional aluminum casting (holding) furnaces is used up for its main purpose -- alloying and maintaining the metal set point temperature. As the metal introduced to furnace is most often already in the molten phase, most of the energy supplied via open fire burners is usually lost through the furnace walls, door openings and the flue gas. In this theoretical study, fire-tubes are immersed in the metal as an alternative for the conventional open fire burners. Using the Finite Volume Method (FVM), Computational Fluid Dynamics (CFD) models, with heat transfer and combustion incorporated, are developed for both design options, using the commercial code StarCCM+. Thermodynamic analyses are adapted in making a comparison between both designs. In both options, the non-premixed flame (heat source) is simulated using the Eddy Break Up (EBU), 3-step reaction models. The participating media radiation models are adapted for a comprehensive estimation of the radiation heat transfer within the furnace. Turbulence within the flame is modeled using the standard K-epsilon model. Results show that the immersed fire tube improved the furnace's thermal efficiency.

INTRODUCTION

The casting furnace is undoubtedly a pivotal equipment in the primary aluminum production plant. Its major function is to collect molten metal from the electrolytic cell and hold its temperature to the metal set temperature while some scrap and alloys are added. Prior to casting, this thermal conditioning is required for the various metal preparation activities such as: alloying, mixing, fluxing and skimming, which are necessary for a high-quality final aluminum product [1]. In the conventional natural gas reverberatory furnace, the molten aluminum is charged directly into the furnace and natural gas flames are fired directly over the metal surface. As the predominant heat transfer means is via radiation, the non-premixed flame is preferred since it allows for a longer flame and hence larger surface area -- which provides uniform temperature across the metal surface. Evidently, at such high temperatures (around 1800˚C flame temperature), radiation is very effective for heat transfer. However, this method of heating has a disadvantage of drastically increasing the metal's surface temperature, resulting in significant dross (skim) generation and in melt loss due to oxidation of the molten aluminum [2]. As the formed oxide layers and skims have relatively low emissivity and thermal conductivity, they act like thermal barriers to the flame which greatly reduces the thermal efficiency of the furnace. The anticipation to increase the metal holding efficiency by using regenerative burners may make the situation even worse by super heating the metal surface, [3].

In the heating and treatment of molten aluminum, immersion heaters are applicable as, for the most part, involves no problem since electrical or fire-tube heaters can be employed and protected from the molten aluminum by housing in suitable refractory materials [4]. By immersing the fire-tube heaters into the metal, the heat transfer mechanism, from the burner to the metal, is predominantly via conduction. These types of heaters are usually used for small furnaces and have previously been proposed for the aluminum smelting industry [2, 4]. However, no large scale implementation has been cited.

Undoubtedly, from the perspective of skim production and metal loss due to oxidation, the fire-tube immersion heater is more advantageous than its open flame counterpart. Furthermore, the immersion of the tubes into the metal can enhance mixing of the metal via natural convection. However, as the mode of heat transfer is mainly via conduction, the thermal efficiency of these burners can be limited by the resistivity of the housing refractory materials and thermal contact resistance. As such, the thermal efficiency of these heaters cannot be quantitatively compared to that of the open fire burners without a comprehensive study. The hazardous nature of the operating furnace coupled with the cost implication of building a model immersion heater powered furnace, makes the experimentation route unfeasible. However, the use of CFD models serves as a reasonable alternative in making this comparison. To achieve this, the multi-physics problem – fluid dynamics, combustion, and heat transfer — inherent in the operation of the furnace, has be modeled and solved for both furnace heating options.

The practice of modeling the aluminum casting furnace is now over two decades old -- it can be traced back to the works of Bui and Ouellet [1]. In their study, a mathematical model of the furnace was used to deduce an optimal fuel control. To achieve this, Bui and Ouellet discretized the furnace into 60 slices, derived a simplified nonlinear control model from the constitutive analytic equations and solved the resulting 60^{th}–order nonlinear equations using Pontryagin's maximum principle. Since then, advancement in the computational modeling field has made this process less tedious. This advancement has encouraged the development of numerous CFD models of the aluminum holding and melting furnace [5, 6]. However, most of these studies have focused on improving thermal efficiency by either optimizing the combustion process [7, 8, 9, 10] or the burners' configuration – height, angle or swirl [11]. To our knowledge, no model which focuses on the use of the immersion heater, for large scale aluminum production, is available in the literature.

The main objective of the present study is to compare the thermal efficiency of the open fire and immersion heater furnaces, of the same capacity, with the same metal charge and, in the same furnace environment. To achieve this, CFD models of the furnace are developed with the two heating options separately implemented. These models are then used to carry out thermal analysis to deduce the respective efficiencies.

MATHEMATICAL MODEL

To estimate the thermal efficiency of each firing option, a full scale CFD model of a 40-ton aluminum casting furnace, measuring 4.5 x 3.3 x 1.7 m, is developed on the commercial code Star CCM+. Figures 1 and 2 show the 3-D and section views of the respective furnace models. Each furnace model consists of 3 domains; combustion gas, molten metal and refractory bricks. The combustion gas domain is modeled using the EBU model. The EBU combustion model works by tracking individual mean species concentration on the grid through the transport equations. The transport equation is facilitated by the 3 step segregated species reaction flow models, for the natural gas fuel, as shown in equations 1-3:

$$CH_4 + 0.5\,O_2 \rightarrow CO + 2H_2 \quad 1$$
$$CO + 0.5\,O_2 \rightarrow CO_2 \quad 2$$
$$H_2 + 0.5O_2 \rightarrow H_2O \quad 3$$

The segregated flow model which solves the flow equations (one for each component of velocity and one for pressure) in an uncoupled manner, is adapted. The linkage between the momentum and continuity equations is achieved with the predictor-corrector method. Turbulence flow is modeled using the standard $k - \varepsilon$ approach — a standard version of the two-equation model that solves transport equations for the turbulent kinetic energy k and its dissipation rate. Heat transfer is modeled using the segregated fluid enthalpy model to solve the energy equation with chemical enthalpy as the solved variable. The temperature profile within the region is then computed from enthalpy according to the equation of state. Thermal radiation from the flame to the metal pad and inner furnace walls is modeled using the Participating Media Radiation Model (gray thermal). This approach ensures that the combustion gasses absorb, emit and scatter thermal radiation – which is particularly important to the heat transfer in furnaces and combustion chambers burning any fuel. The total emissivity of the combustion gases are estimated to be 0.15 from the emissivity charts presented in the reference [12]. Other gas temporal properties utilized in this study — density, molecular weight, specific heat, thermal conductivity, Prandtl number and viscosity-- are available in the reference [13].

The molten metal domain is modeled as a liquid using the segregated flow and enthalpy models. The emissivity of the metal's top surface is set at about 0.1 and all other properties are defined as a function of temperature as presented in [13]. The furnace refractory walls are modeled as a solid region, with an emissivity of 0.8. The material properties-- density, thermal resistance and specific heat -- are obtained from the manufacturers [14]. The exterior surfaces of the furnace walls are modeled to be in a free convection environment, with an ambient temperature of 40˚C and heat transfer coefficient of $3W/m^2K$. These boundary conditions are similar to the conditions in a cast room.

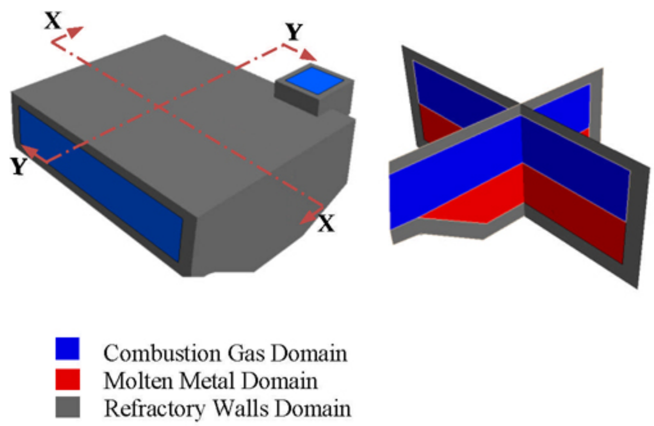

Fig 1: Domains of the Open fire Furnace

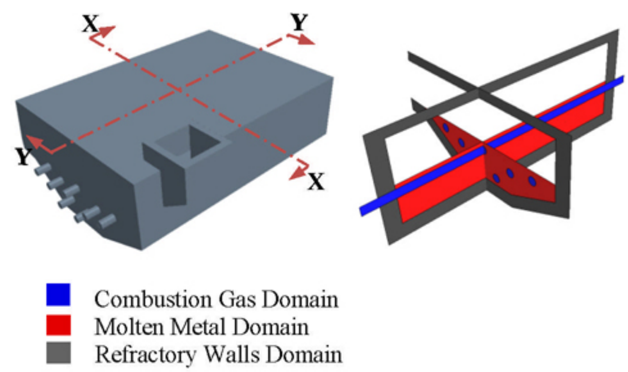

Fig 2: Domains of the Immersed Heater Furnace

The open flame heating design consists of two non-premixed burners each with air and fuel flow rates of $0.2069 kg/s$ and $0.0119 kg/s$ respectively. Both the air and fuel are supplied at standard ambient temperature and pressure (25˚C and 100kPa). As shown in Fig 3, the burners are located above the metal pad's surface, at the end adjacent to the exhaust's duct location. At this location, the burners fire into the "furnace gas" region which heats up the furnace walls and metal pad surfaces via radiation and convection. The combustion gasses then exit the furnace via the exhaust vent that is located at the other end, after sweeping through the furnace length. This is a typical design which is adopted in order to maximize the combustion gases' resident time in the furnace.

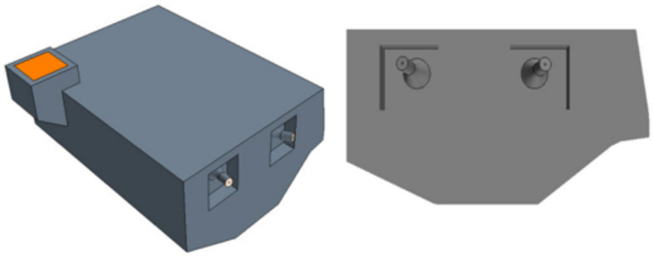

Fig 3: Open fire Burners

On the other hand, in the immersion burner design, 7 immersed burners are adapted, in order to ensure temperature uniformity within the metal's cross section. To ensure parity with the combustion capacity of the open fire burner, the air and fuel flow rates for each of the immersed burner is adjusted to $0.05911 kg/s$ and $0.0034 kg/s$ respectively. In this design, the fire tube burners are distributed across the metal, in the longitudinal direction, as shown in Fig 4. Ceramic fire-tubes are used to house the burner's hot gases in order to avoid the flame's direct contact with the metal. This housing also serves as a path to transport the hot combustion gasses from one end of the furnace to the other. The fire tube has a thickness of $0.0125m$, density of $2560 kg/m^3$, thermal conductivity of $15.72 W/m.K$ and a specific heat of $1171.52 J/kg.K$. For a more effective heat exchange rate, the burners are placed at the opposite ends of the furnace such that the combustion gases are ran in a counter flow.

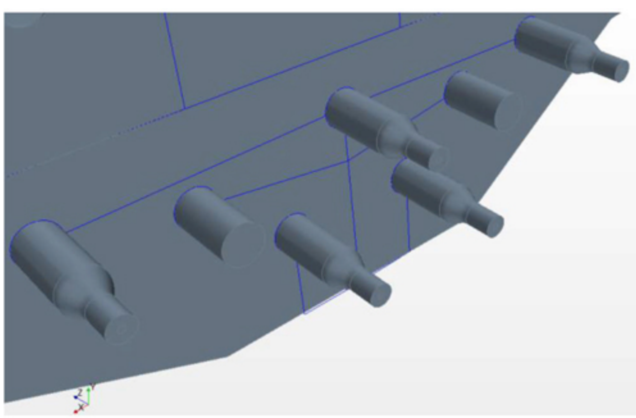

Fig 4: Immersion heater burner

In both models, polyhedral grids with a base size of 0.05m are adapted for the mesh continuum. This mesh size is based on the mesh sensitivity analysis carried out for the open fire burner model, as shown in Fig 5. Fig 5 shows the heat flow to the furnace walls – via convection and radiation – as the number of elements increases. From the figure, it can be seen that mesh convergence begins at about 1 million elements which coincides with a mesh size of 0.05m.

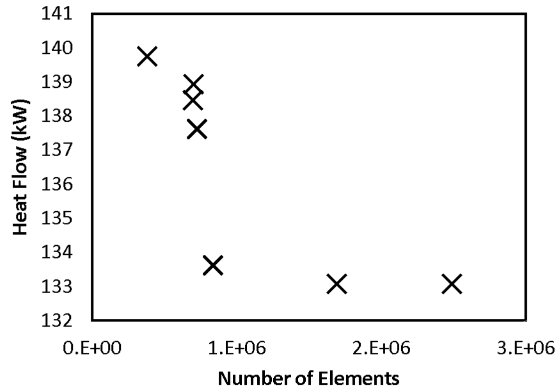

Fig 5: Mesh Sensitivity Analysis

RESULTS

Fig 6 shows the velocity profile of the combustion gases in the furnace with the open fire burners. The model's estimate of the burner's nozzle exit velocity is about 65m/s which is only about 3% less than the analytically estimated value. Furthermore, the model's estimate of the mass flow rate, at the exhaust outlet, is 0.437kg/s — portraying an accurate conservation of mass within the furnace.

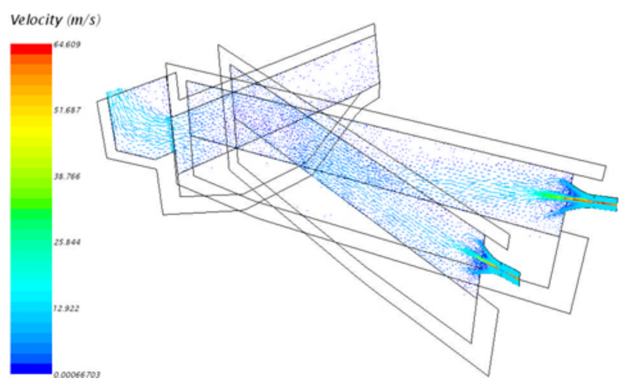

Fig 6: Velocity Profile (Open fire Burner)

The fuel's mole fraction within the open fire furnace, is shown in Fig 7. The figure shows that the fuel continuously depletes as it travels further into the furnace. This is as a result of the chemical reaction between the fuel and air progressing into the furnace until the fuel completely combusted. The observed trend depicts the ideal behavior of a non-premixed flame. The estimated mass concentration of the exhaust gas species are: 8.9% CO_2, 17.2% H_2O, 2.5% O_2, and 71.2% N_2. As the initial feed contained about 2% excess air, the accuracy of our model's estimation of the chemical reaction can be said to be above 80%. Although a fair idea of the flame's shape and length can be deducted from the mole fraction of the fuel, the furnace's temperature contour in Fig 8 elucidates more on these flame distribution properties.

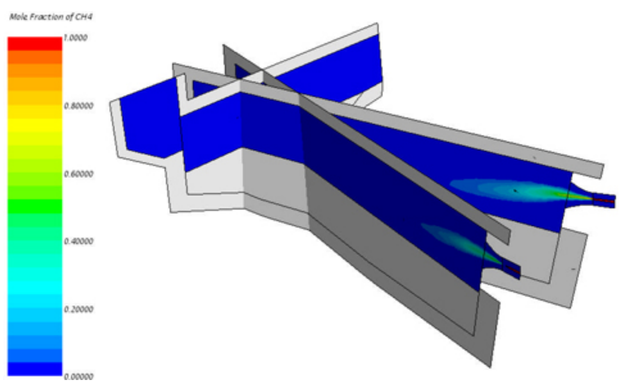

Fig 7: Mole Fraction of CH4 (Open fire Burner)

The Fig 8 shows that the estimated flame temperature is about $1900^{\circ}C$ which is in close correlation with the values available in the literature [15, 3]. The total heat of combustion was also found to be in close correlation with the values obtained using an analytical approach —only about 7% less than the theoretical value. Furthermore, the flame length is measured from this temperature profile to be $2.77m$—which is only about 15% less than the length estimated from the Delichatsios' correlation [16].

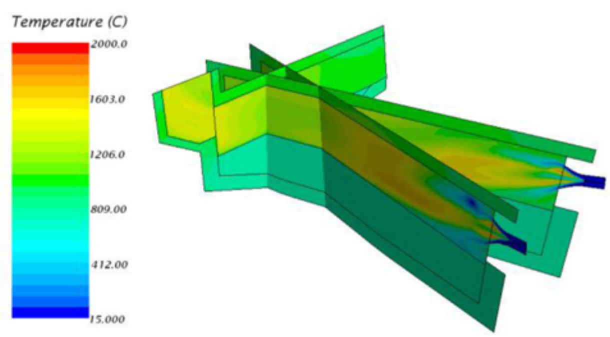

Fig 8: Temperature Profile (Open fire Burner)

To validate our radiation heat transfer model, the metal pad's surface temperature is fixed and a simplified model is developed for the furnace using Engineering Equation Solver (EES). The simplified model considers a two isothermal surface enclosure (grey) – metal pad and furnace walls—with a grey gas contained between them. The equivalent network is deduced and the resulting equations are solved simultaneously. In comparison to our CFD model's solution of the same problem, the EES model depicted only a 6% deviation.

Fig 9- Fig **11** show the corresponding velocity, fuel mole fraction and temperature profiles, respectively, as calculated by the immersed fire-tubes burners' model. This model's results -- nozzle exit velocity, exhaust mole fraction, flame temperature and heat of combustion-- are also in close correlation with values presented in literature.

Based on the basic thermal efficiency relation (heat transferred to the metal pad / heat supplied by burner) the thermal efficiency of both options are estimated, for a metal pad temperature range of 700-850˚C.

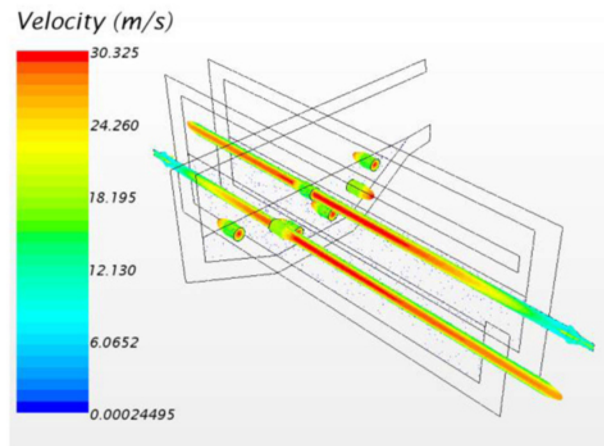

Fig 9: Velocity Profile (Open fire Burner)

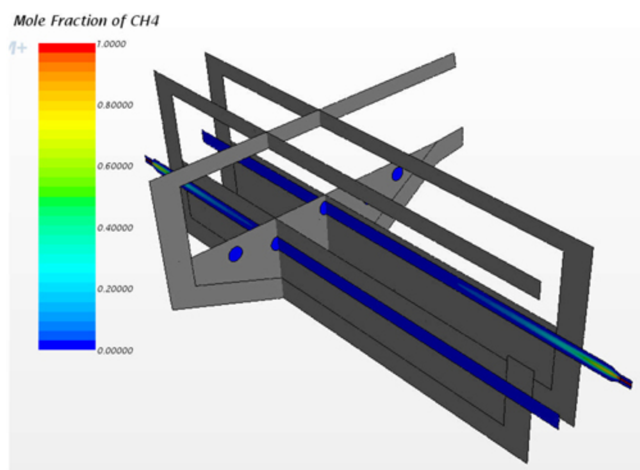

Fig 10: Mole Fraction of CH4 (Open fire Burner)

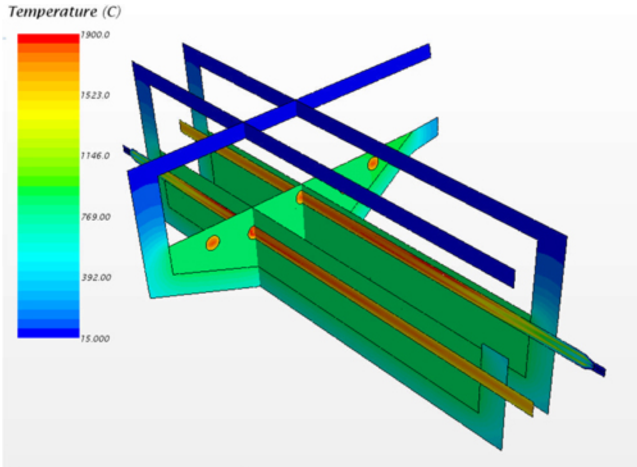

Fig 11: Temperature Profile (Open fire Burner)

Fig 12 shows that across this temperature range, the furnace's thermal efficiency with the immersed heater is about 2-3 times greater than that of the open fire burner. In this temperature range, the open fire burner showed only 5.24-4.47 BTU/hr/lb [12.18-10.4 kJ/hr.kg] of heat transfer rate to molten metal. On the other hand, the immersed heaters transfer heat to the metal with rate of 14.58-13.39Btu/hr/lb [33.9-31.14 kJ/hr.kg]. The corresponding values of fuel's energy consumption for one batch was 47.2 Btu/hr.lb [109.8 kJ/hr.kg]. Based on this energy consumption rates, the calculated energy utilization (energy thermal efficiency) in the open fire case will be about 10% and for the immersion heaters will be about 28%. This increase of the energy utilization would save up to 2/3 of the current gas consumption. The open fire results are in good correlation with the findings reported in the reference [2]. The onsite measurements [17, 18] have shown that the open fire holding furnaces efficiency is around 11-12%, which is also in good correlation with our findings. The reason for this can be attributed to low emissivity of the metal pad's surface due to the high temperature oxidation.

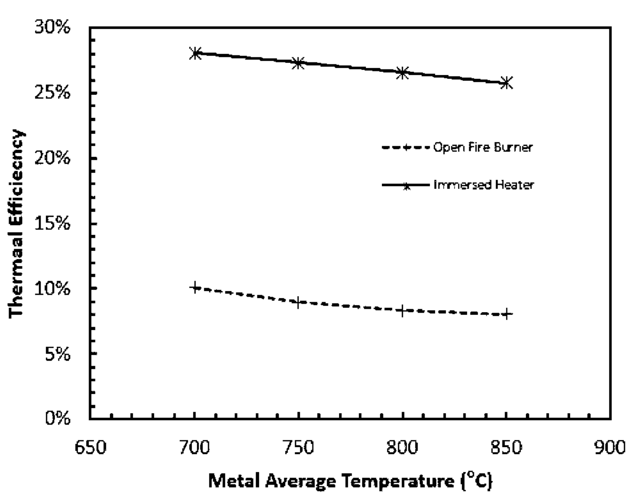

Fig 12: Thermal Efficiency comparison between the open fire and immersion heater.

CONCLUSION

3D CFD model, with combustion and heat transfer, are developed for 40-ton aluminum holding gas-fired furnace, using the commercial code StarCCM+. The open fire and immersed fire-tubes burners are separately implemented in the furnace models. Mesh sensitivity analyses and comparison with data available in literature suggests the validity of our models. Thermal efficiency comparison between the open fire burner and the immersion fire-tube heater is performed. The results showed that at the temperature range of 700-850˚C, the immersion heater is about 2-3 times more efficient than the open fire burner.

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