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A comparison between tuyere core types – cooling efficiency and manufacturability

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Abstract

Tuyeres in blast furnaces are exposed to extreme temperatures between 1900 and 2300°C. It is therefore important to cool the tuyere in order to reduce the risk of failure caused by high temperatures. In this study, CFD and experimental investigation are performed to observe and record the effect of roughness between three different common techniques of creating cavities in tuyere castings; sand cores, copper pipes and glass cores. The roughness values for each were measured using a profilometer then converted to their respective sand grain roughness values and used as part of a CFD simulation to calculate the pressure drop and heat transfer of each core type. It is shown that the rougher the surface, the more the roughness elements protrude through the laminar sublayer, thus the higher the turbulent intensity at the wall and the higher the heat flux. The sand core was as high as 17-20% larger in heat flux than the copper pipe and glass pipe cores with as little as a 2-3% pressure drop increase. Flows were also identified to be transitionally turbulent meaning the viscous effects from the laminar sublayer are present. An accurate model to measure the effects of the roughness on pressure drop and heat transfer is developed and evaluated. A manufacturing perspective on each core type is also discussed in providing additional information on the relationship between manufacture and cooling efficiency.

Keywords: Surface roughness; boundary layer, heat transfer, pressure drop, tuyeres

1 Introduction

A blast furnace tuyere is a high purity, water cooled, copper nozzle which blows a hot blast into the hearth of a blast furnace. This hot blast is first heated in a stove between 1000 and 1300°C and delivered to the furnace via the hot blast main, bustle pipe, tuyere stock and finally the tuyere itself. The hot blast reacts with coke and injectants and forms the raceway in front of the tuyere. A huge amount of heat is generated in the raceway due to combustion of coke and injectants which leads to temperatures between 1900 and 2300°C [1]. It is important then to sufficiently cool the tuyere to prolong its life in service. Tuyere waterways come in few shapes and sizes and usually consist of a pipe and a jacket. The pipe is located at the hottest end of the tuyere where higher velocities are needed for improved convection. The way the pipe cavity is formed can lead to different channel shapes and roughness values as a result of the manufacturing technique. Inner cores are used for implementing the cavities of any kind and shape into the casting. Inner cores are generally referred to as cores; usage of the expression “inner core” is only recommended if both an inner and an outer core is present in the same casting [2].

The three main cores which generate the cavities are sand, copper and glass, each have their benefits and drawbacks regarding manufacturability and operational efficiency. A sand core is quickly made although has restrictions in its shape and can produce “finning” on the cavity walls, a phenomenon whereby metal penetrates the wall during casting leaving a fin like shape. A copper pipe core stays in the casting and relies on a good bond between the pipe and liquid copper during solidification. This problem has been discussed in previous work and is thought to influence the overall heat transfer by creating a small insulating layer [3]. Glass pipes maintain a circular cross section and are easily removed from the casting however their cost and lead time is typically higher. Each core produces different wall roughness in the tuyere cavity.

Nikuradse [4] investigated the effect of wall roughness on turbulent flows by measuring pressure drop using uniform sand roughness. His detailed experiments and insights set the stage for predication of rough-wall flows. Colebrook [5] extended this work to include commercial pipes and Moody [6] collected this information and put it into graphical form to be used by practitioners. Schlichting [7] developed detailed work on the boundary layer which is now used by simulation software to predict all types of flow.

Various studies including Ceylan [8] concluded that roughness was of major importance for convective heat transfer. Flack [9] also concluded that the roughness effects are mostly confined to the inner layer on the law of the wall graph and the outer layer is insensitive to surface condition except in the role it plays in setting the length and velocity scales for the outer flow.

The aim of this study is to provide insight to which core provides the highest heat flux and reduce the risk of temperature dependent failure of the tuyeres. How each waterway manufacturing technique affects heat transfer will be balanced against the design for manufacture.

2 Experimental methodology

2.1 Sample manufacture

Two sets of three 300mm long samples were cast at Peel Jones Copper Products Ltd which included each of the three cores. The hydraulic diameter of all samples was 25mm. Sample length was restricted by the available tube furnace size. Typical nose waterways are actually 1 to 2 meters in length. Sections of samples were cut to measure the surface roughness using a profilometer on each cavity to get the centerline average roughness height of the surface (Ra) and the difference between the tallest peak and deepest valley (Rz). The equivalent sand grain roughness (Ks) was calculated from both average centerline surface roughness (Ks-Ra) and maximum displacement (Ks-Rz). It should be noted that the copper pipe core is smoother as it is a drawn copper surface whereas the other surfaces are cast surfaces.

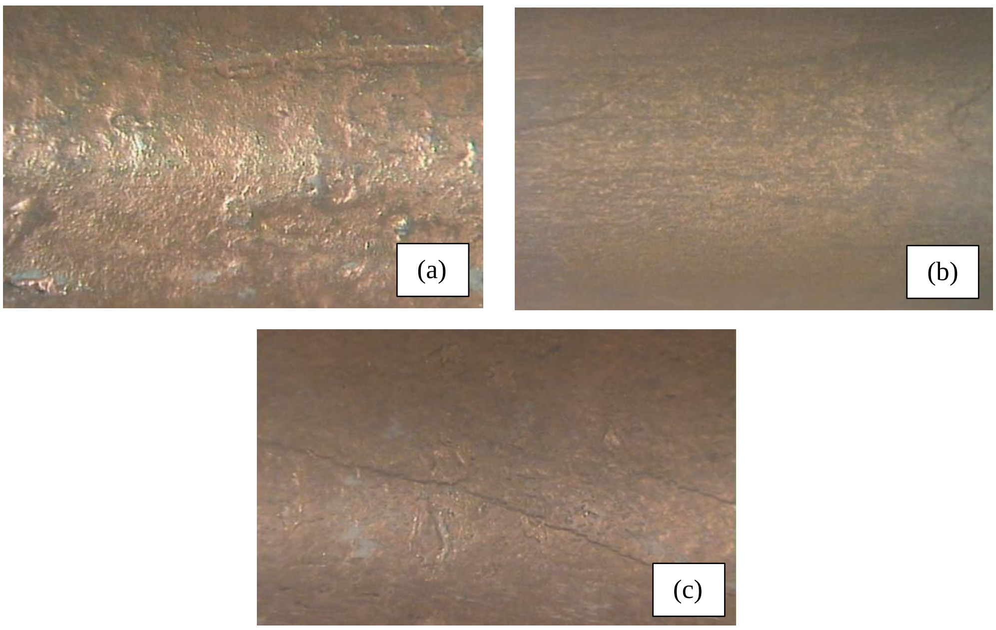

Figure 1. (a) Sand cored surface; (b) Copper pipe surface; (c) Glass cored surface

Table 1. A table showing measured surface roughness values of each pipe core

Pipe core	Ra (μm)	Ks-Ra (μm)	Rz (μm)	Ks-Rz (μm)	Relative roughness Ks-Rz/D
Sand	4.0	23.5	20.53	20.1	8.03E-04
Copper	1.4	8.21	7.7	7.53	3.01E-04
Glass	1.8	10.6	11.6	11.3	4.54E-04

2.2 Flow test setup

Waterway diameters were chosen to represent common blast furnace practice, the surface roughness rig did not attempt to mimic blast furnace flow rates and total pressure drops. The manufactured samples are placed one by one into a tube furnace with insulated packing underneath to centralize the sample. The sample is then connected to a flow system which has an average inlet flow of 8.5 L/m and an outlet leading to atmospheric pressure, this flow would be transitional with a Reynolds number of approximately 8000. Since the experimental flow rate is small, this setup understates the effect of surface roughness and so heat exchange between the furnace and the flow should be higher in an operating tuyere. A higher flow rate of 30 L/m was used but gave no noticeable difference in temperature. The experiment is not comparable to an actual blast furnace installation as the aim was to compare the effects of surface roughness.

The furnace was heated up to 600°C on each sample and the outlet temperature of the flow was recorded in increments using a K-type thermocouple as the temperature ramped up from room temperature.

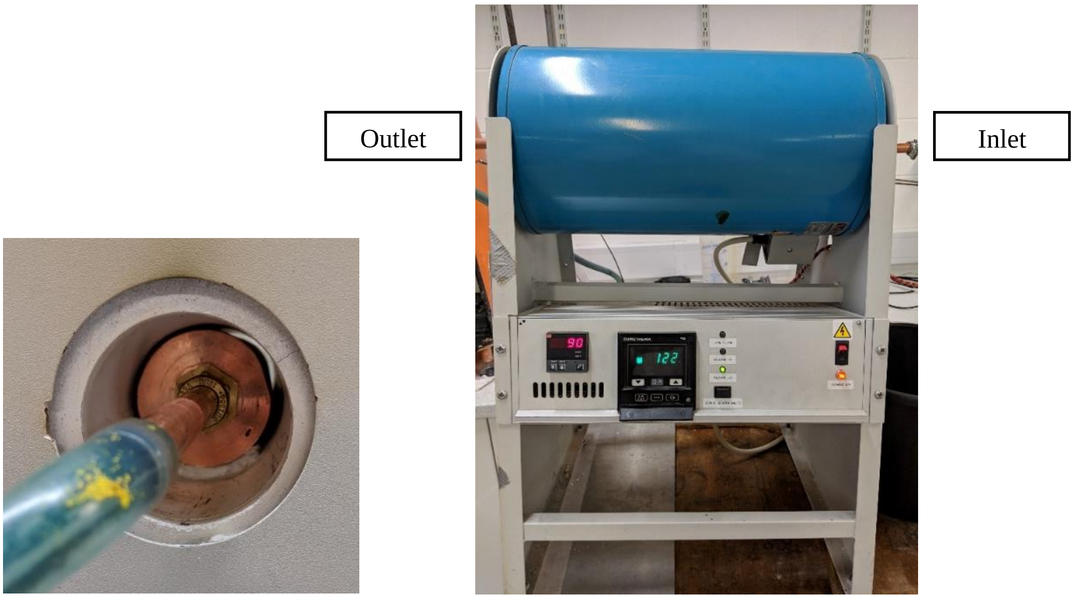

Figure 2. (a) sample inside tube furnace; (b) tube furnace

3 CFD simulation methodology

3.1 Flow solver

The flow was modelled numerically by solving for steady state incompressible Reynolds-averaged Navier-stokes (RANS) equations. ANSYS Fluent V19.1 is used in this study. The pressure-based coupler solver is chosen as it is known to be more robust and better at converging in low Reynolds number cases [10]. The solver is run for 3000 iterations where the converging values are within 10^{-4}.

3.2 Model setup

The simulation is done to mimic that of a typical tuyere pipe as much as possible whilst maintaining a simple straight pipe model for faster simulation times. The diameter and length of the model is 25mm and 1m respectively. The inlet velocity is set to 18 m/s and the outlet pressure is to atmosphere. For the purpose of measuring pressure drop and heat transfer across three different pipes of different roughness values, the model is simplified to a two-dimensional analysis. Energy is enabled in the model and a temperature is added on the zero-thickness wall of 363 K with a water inlet temperature of 300 K. The sand grain-roughness (Ks-Rz) is required as an input for the walls. Previous work on calculating sand grain roughness from geometric roughness shows that the Rz value is more accurate in determining the sand grain roughness [11]. A copy of the copper pipe model is also simulated with varying air gap thicknesses of 0.000001mm, 0.001mm and 0.1mm.

3.3 Turbulence model

Since the viscous and drag forces close to the wall are being resolved, a low-Re viscous model is used to correctly reproduce the limiting behaviors of various flow quantities as the distance to the wall approaches zero [12]. The SST 4-equation transition model is chosen which is used where highly accurate resolution of the boundary layer and heat transfer profile is required. The model constants within the viscous model are set to their default and a roughness correlation is added using the geometric roughness height (Ra). When roughness is simulated, the model uses an empirical correlation which corrects the local transition momentum thickness and is used to calculate a new critical Reynolds number and transition length function [13].

3.4 Computational Domain

Automatic mesh of element size 0.0015m is generated. An inflation from the walls to resolve the laminar sublayer within the simulation is used in the mesh. The first cell height estimation of the inflation can be calculated using the following method, where ΔS is the first cell height,

$$\Delta S = \frac{\mu y^+}{\rho u_\tau} \tag{1}$$

To solve for the laminar sublayer the following condition should be met $y^+ = 1$. The symbol u_f is the friction velocity and is determined by,

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}} \tag{2}$$

Where τ_w the wall is shear stress is found using the equation,

$$\tau_w = \frac{\rho U^2 C_f}{2} \quad (3)$$

The skin friction coefficient is empirically found and so has numerous formulas, but ANSYS [13] recommends the internal flow formula for C_f which is,

$$C_f = 0.079 \times Re^{-0.25} \quad (4)$$

The Reynolds number (Re) is the ratio of inertial to viscous forces and is a dimensionless number. The formula for this is shown below.

$$Re = \frac{\rho \upsilon D}{\mu} \quad (5)$$

Where ρ the density of water, υ is the velocity, D is the diameter and μ is the dynamic viscosity. Working out the velocity from the flow rate and pipe diameter then allows Re to be calculated which gives a value of approximately 5×10^5 which indicates the flow is turbulent.

Aligning the calculated Re with the relative roughness from table 1 onto the moody chart shown in figure 3 shows that the flow is transitionally turbulent, meaning wall shear stresses arise both from viscosity and pressure drag on the roughness elements and so therefore the friction factor used to calculate pressure drop is a function of both. It also means there is still a laminar sublayer present at the wall. Moody expected the friction factor from this diagram to be within 10% accuracy [9].

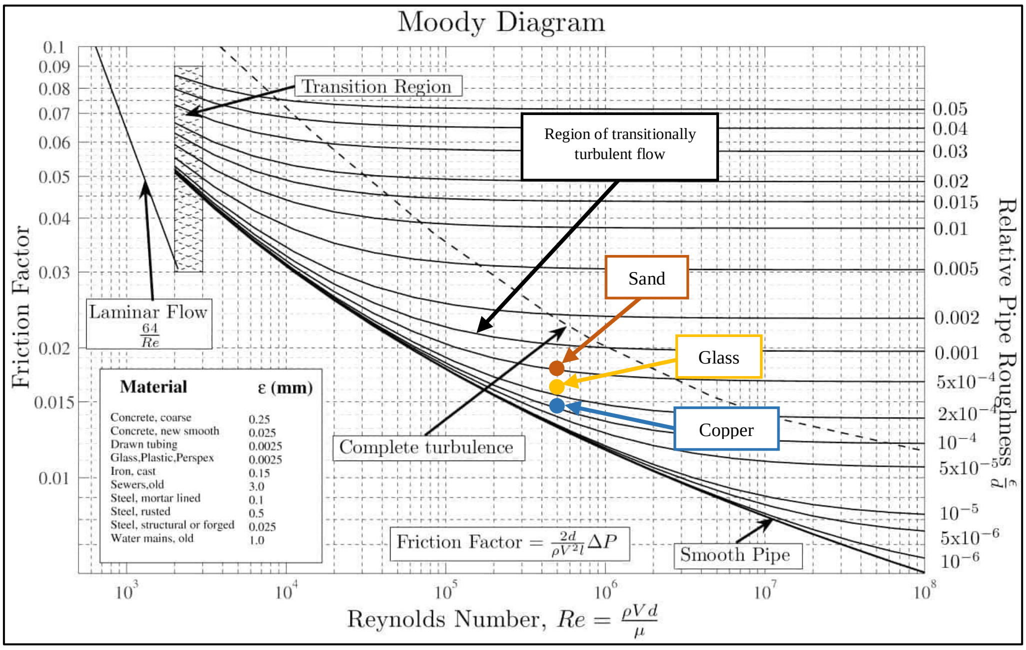

Figure 3. Moody chart showing the area in which the flow characteristics act

According to Schlichting [7] the influence of the wall is characterised by $K_s^+ = u_\tau k_s \rho / \mu$ which is a dimensionless flow quantity. From this the roughness can be divided up into three regimes:

- Hydraulically smooth ($K_s^+ \leq 5$)
- Transitional ($5 < K_s^+ \leq 70$)
- Fully rough ($K_s^+ > 70$)

According to the data provided by Schlichting [7], roughness effects are negligible in the hydraulically smooth regime and are no different to a smooth surface, but become increasingly important in the transitional regime, and take full effect in the fully rough regime whereby the viscosity effects vanish and so the flow becomes independent of the Reynolds number. The K_s^+ values are therefore estimated and are shown in table 2 which will be re-calculated based on CFD simulation results for validation. Initial estimated values show the flow regimes are all transitional with the sand core value 2 to 3 times larger than the other cores meaning the laminar sublayer will be smaller in height.

Table 2. Table showing the flow regime based on measured roughness and estimated Ks+ values

Pipe core	**Estimated K_s^+ F**	**Regime**
Sand	15.63	Transitional
Copper	5.86	Transitional
Glass	8.83	Transitional

4 Results

4.1 Experimental results

The three samples with roughness values (Ra) of 4.0 (sand), 1.4 (copper) and 1.8 µm (glass) were investigated under transitional flow conditions. Temperature difference (ΔT) between the inlet and outlet water flow for each sample are shown in figure 6.

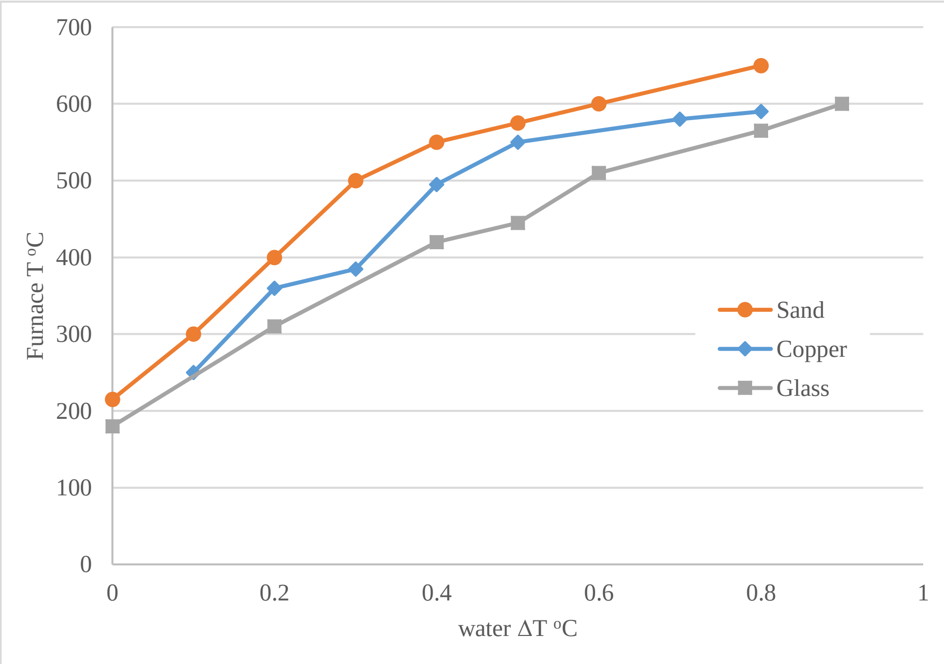

Figure 4. Graph showing temperature difference between inlet and outlet vs the furnace temperature

4.2 CFD simulation results

The results gathered from the simulation include across each core type, the pressure drop, inlet and outlet temperature difference, centerline velocity, wall heat fluxes, wall shear stresses and newly calculated values of K_s^+ based on results.

Table 3. Table showing new Ks+ values based on simulation results

Pipe core	Estimated K_s^+ F	Simulation K_s^+	Regime
Sand	15.63	20.18	Transitional
Copper	5.86	7.10	Transitional
Glass	8.83	10.73	Transitional

Table 4. Table showing simulated pressures and heat exchange of each pipe

Pipe core	Total pressure drop (Pa)	ΔT (℃)	Total heat transfer rate (W)
Sand	124571	16.62	5280891
Copper	119706	15.3	4429769
Glass	121335	15.2	4546110
0.000001mm air gap	-	15.3	4416939
0.001mm air gap	-	4.05	1134392
0.1mm air gap	-	0.05	15194

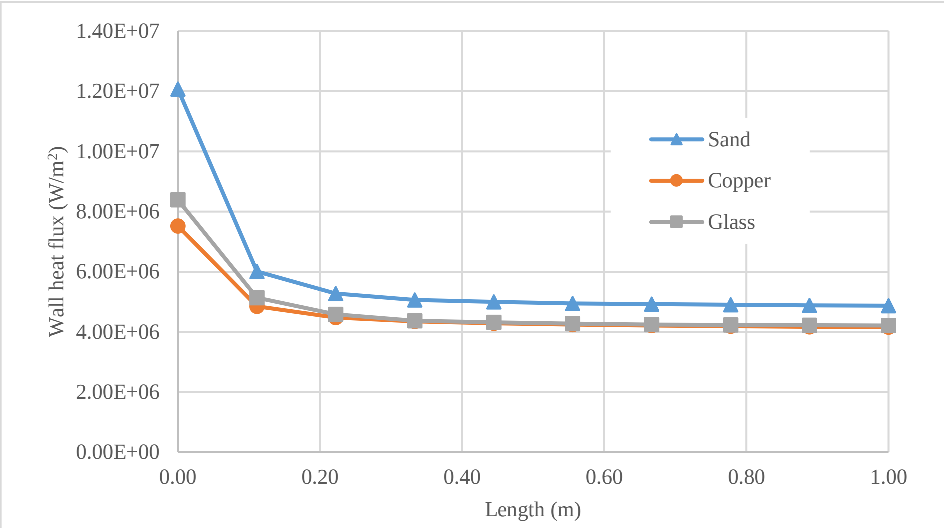

Figure 6. Graph showing comparison between wall heat fluxes on the three different samples

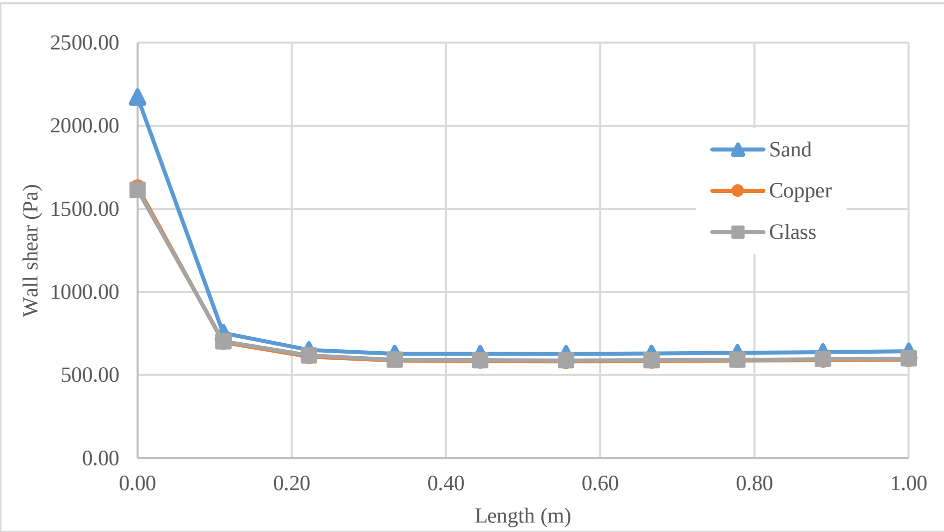

Figure 5. Graph showing comparison between wall shear on the three different samples

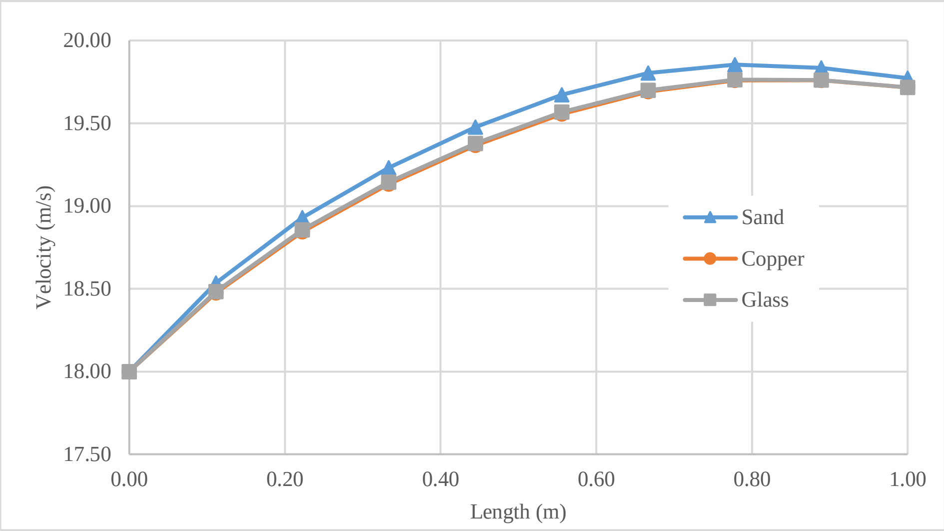

Figure 7. Graph showing comparison between centreline velocities on the three different samples

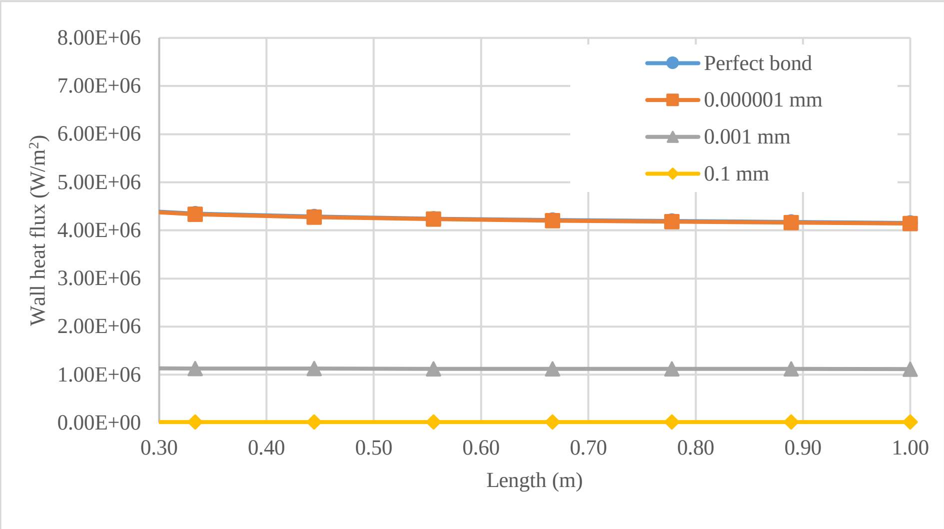

Figure 8. Graph showing the effect of different air gap thicknesses on wall heat flux

5 Discussion

Each method of creating the cavity within a tuyere has its benefits and drawbacks, these will be explained in detail from a technical point regarding which design is more efficient based on the known variables such as roughness effects, lack of bond during casting and cross-sectional area. They will also be explained from the manufacturing perspective and how each design is affected to meet manufacturing requirements and what effect this has on the flow and heat transfer.

It can be observed from the sectioned samples that the sand cored sample had the highest average surface roughness (Ra) of 4.0 μm as well as larger peaks and troughs (Rz) of 20.53 μm. The copper and glass samples were close in roughness values with a Ra of 1.4 and 1.8 μm and an Rz of 7.7 and 11.6 μm respectively. The copper pipe is both smoother than the other samples and more uniform in its roughness, with the glass slightly ahead in both Ra and Rz values. Centered on the work done by Moody and Schlichting it is noticeable that based on the measured roughness values and calculated Reynolds number the waterway flows are within a transitional region of turbulent flow meaning that the viscous and drag effects on the flow are both present due to the existence of what is known as the laminar sublayer. The laminar sublayer exists at the interface of the wall and the flow, it provides the main resistance to heat transfer from the tube wall to the bulk of circulating water [14]. The thickness of the laminar sublayer is smaller the higher the Reynolds number is, since the Reynolds number doesn't change between each core the roughness is the only thing which effects this layer thickness. New calculated values of K_s^+ based on simulation results verify the flow for all three pipe cores is transitionally turbulent as shown in table 3.

In the experiment it was found there is very little temperature difference between the inlet and outlet of the three samples as can be seen in figure 5. Although the furnace temperature was 600℃ the surface temperature of the copper castings, measured by a radiation pyrometer, did not exceed 50℃ across the three samples. Results followed a clear trend and there is less than 1℃ change in flow temperature across the 400℃ temperature range showing a high degree of efficiency of the samples heat transfer. The Steel Industry Metallurgical Committee (SIMEC) specification dictates that a good metallurgical bond exists for at least 80% by area of the interface between the copper pipe and the casting. The lack of bond must be visible on an x-ray conducted to ASTM E272. There was no visible lack of bond on the copper pipe used in this experiment. Previous experience suggests if the sections were polished to a 1 µm diamond finish it is likely that the lack of bond would be visible to the naked eye or at low magnifications. Even if not visible in a corresponding radiograph.

Simulation results show that as the sand grain roughness increases, the wall heat fluxes also do, which leads to an increase in temperature difference between the inlet and outlet (ΔT) and thus a higher total heat transfer rate as shown in table 4. They also show that the rougher the surface, the higher the centerline velocity. The wall shear also corresponds to the pressure drop values between each core correctly, with a higher shear leading to a higher pressure drop.

5.1 Sand Cored waterways

The results from the simulation using the calculated equivalent sand grain roughness values show that the pressure drop is 2-4% higher in the sand core simulation in comparison to the copper and glass pipe core, the average heat flux at the wall is 17-20% higher than the copper and glass pipe core simulations which is represented in figure 6. The simulation does not take into account "finning" a phenomenon where metal penetrates the core leaving a fin like protrusion which would cause some additional drop in pressure, and an expected increase in heat transfer. The sand core products are expected to have a larger variation in roughness values than the other cores, nevertheless the heat transfer and pressure drop of sand cored waterways should always be higher than the copper pipe waterway and glass cored waterway. It is possible that 3D printed sand cores would show less variation but the cost of these cores is not yet supported by the customer base. Tuyeres with sand cored nose pipe channels could be within a region of completely turbulent/fully rough flow rather than transitionally turbulent flow as a result of finning and roughness variation, thus completely removing the laminar sublayer which behaves as an insulator. Across a full tuyere other manufacturing limitations exist including changes in cross section and the addition of structural supports for the sand core during manufacture, causing further differences in flow.

5.2 Copper Cored Waterways

The copper core products typically have much smoother and more uniform surface roughness as can be seen in figure 1. Simulation results show a smaller drop in pressure and less heat flux at the wall due to the thicker laminar sublayer and less turbulent intensity near the wall as a result of less wall shear. The copper pipe core has the additional vulnerability of achieving a poor bond with the casting, the simulation showed that with a very thin layer of air at 0.000001mm in size the heat flux and total transfer rate was affected by an insignificant amount with an average difference of just 0.3% in wall heat flux values as can be seen in figure 9. However, as the gap increased in thickness, the heat flux reduced exponentially with a 77.6% decrease in heat flux at 0.001mm thickness and a 99.8% at 0.1mm thickness, meaning the total heat transfer rate as shown becomes critically low as shown in table 4, at this point any tuyere would fail.

5.3 *Glass Cored Waterways*

The glass core sample is very similar to the copper pipe core and is also very uniform in surface roughness whilst having slightly larger roughness elements causing a minor raise in pressure drop and in heat flux at the walls. It appears to be the optimum core material but this type of pipe is considered a specialized product at Peel Jones Copper Products Ltd as a result of limited pipe availability and costly glass removal methods, the cost and lead times are substantially increased on products made using this method and perhaps they are only justified for very hard driven furnaces.

6 Conclusion

The results prove the theory that with an increase in surface roughness there is an increase in heat transfer within the system. The sand core simulation based on the sand grain roughness has shown there is little pressure drop difference for a fairly large increase in wall heat flux. It should be taken into consideration however that the addition of other surface effects (finning) on the sand core affect the pressure drop by a potentially significant amount. Naturally occurring or deliberately produced surface roughness can be desirable where high heat transfer is required and this may be the case for a tuyere. More control and understanding of roughness design would help with optimizing pressure drop against heat transfer.

Flows across the three different cored cavities were proved to be within a transitionally turbulent region though it is expected that the sand core would produce a completely turbulent flow in reality, however the copper and glass core likely wouldn’t and stay transitionally turbulent unless flow rates or roughness is increased.

It was shown during the simulations that with a small air gap in between the copper pipe and casting, the heat flux was affected by a negligible amount, but as the air gap increased the heat flux decreased in an exponential fashion.

The copper and glass pipe core samples have room to increase their Reynolds number through increased flow rate to match that of the sand core pressure drop, though in turbulent flow pressure drop varies exponentially with flow rate, meaning it may be more worth artificially increasing surface roughness.

More work could be done on measuring roughness values on castings and understanding the deviation between each casting more as it could have a large effect on heat transfer and more work can be done on exposing test samples with varying roughness in harsher environments to match that of the blast furnace in regards to temperature, this can then be used to validate the simulations.

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