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# HELIUM INFUSION IN SAND MOLDS: MEASUREMENT & ANALYSIS OF HEAT TRANSFER PROPERTIES & MECHANISMS

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## ABSTRACT

*Conventional sand casting is an important manufacturing process that is marred by low solidification rates due to inferior heat transfer properties of the mold material that in turn result into inferior microstructure and mechanical properties of the cast part. This paper reports an increase in heat transfer properties of porous silica sand mold material by helium infusion. Heat transfer properties investigated in helium environment include apparent thermal conductivity and heat diffusivity. Apparent thermal conductivity in both air and helium environments is measured using ASTM E1225 (standard test method for thermal conductivity of solids using guarded comparative longitudinal heat flow technique) at a low temperature range (25°C to 125°C) to safeguard mold integrity and to prevent binder gases' influence on measurements. Value of heat diffusivity is then mathematically deduced at 100°C for simulating the effect of helium presence. Further, a hypothesis is postulated herein for heat transfer mechanism in the porous silica sand mold wherein a case of operationally feasible "continued flow helium infusion" in the sand casting process is mathematically investigated via Biot number analysis. Results show that helium infusion increases the heat transfer properties of porous silica sand mold; the value of apparent thermal conductivity of sand mold specimen is found to be increased ~89% at 25°C and ~99% at 125°C with helium inside the pores as compared to the baseline (without helium) whereas heat diffusivity is shown to increase ~94% at 100°C in comparison to baseline (without helium). The results of experiments are validated at significance level of 0.05 via analysis of variance "ANOVA". Biot number analysis carried out at two hypothetical flow rates of 1 L/min and 4 L/min supports the postulated hypothesis and establish the role of helium flow rate as a new process parameter in helium administered sand casting process.*

***Keywords:*** *Heat transfer mechanism, heat transfer properties, helium infusion, sand mold*

# 1) INTRODUCTION

Sand casting is a versatile manufacturing process for both ferrous and non-ferrous metals that makes use of the expandable sand molds (Kelpakjian, 1995). Its working principle involves pouring of molten metal in a cavity and allowing the metal to solidify; wherein the cavity is produced by making use of a non-expandable pattern which is an imprint of the desired shape (to be cast) along with risers, gating systems and pouring basin etc. (Kelpakjian, 1995)

Despite the many benefits that the process offers, one of the main adverse issues associated with the sand casting process is, the inherently slow cooling/solidification rate that is imposed by the inferior heat transfer properties of molding material through which the heat from the solidifying material must flow to escape outside (Poirier and Geiger, 1994; Poirier and Poirier, 1994). This solidification rate is an extremely important processing parameter in metal casting process, as it influences the microstructure of the cast part (Poirier and Geiger, 1994) that in turn influences the mechanical properties. Secondary dendrite arm spacing (SDAS) and grain size are two of the many microstructure features that become refined with an increased cooling rate (Dobrzanski et al., 2006; Wan and Pehlke, 2004; Zalensas, 2001) and it is an accepted conclusion that other things being constant; a smaller SDAS results in better tensile properties (Dobrzanski et al., 2006; Zhang et al., 2008; Ceschini et al., 2009; Shabestari and Shahri, 2004; Jeong et al., 2008); the overall beneficial effects of grain refinement include less tendency to hot tearing, increased pressure tightness, improved feeding characteristics, consistent properties after heat treatment and finer distribution of secondary phases and porosity (Zalensas, 2001). Figure 1 is the schematic representation of the process.

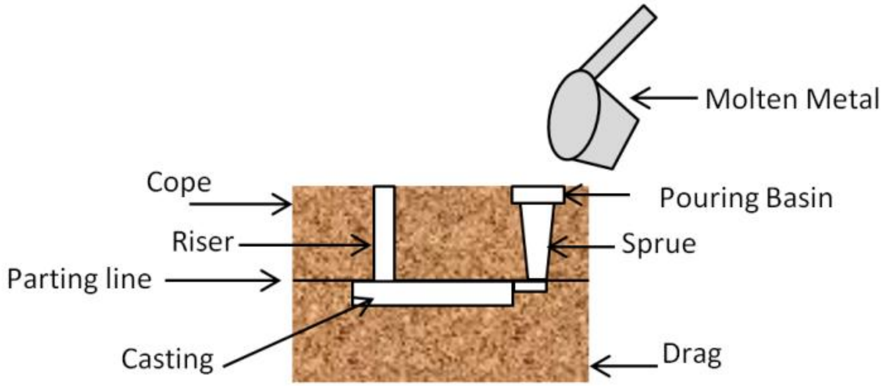


*Figure 1: Schematic Representation of Sand Casting Process (adapted from Kalpakjian, 1995)*

Considering the dynamics of the process and the fact that sand molds have inferior heat transfer properties when compared to metallic molds, it becomes highly beneficial if the heat transfer properties of the sand mold material are improved.

The work reported herein subjects a silica sand mold specimen to helium environment for helium's superior to air, thermal conductivity, and measures the heat transfer properties & analyzes the heat transfer mechanisms. Apparent thermal conductivity measurements are done using the guarded comparative longitudinal heat flow technique (ASTM E1225). A low temperature measurement range of 25°C to 125°C is selected herein for preventing any possible generation of binder gases at high temperatures that could otherwise interfere with the measurements; the physical integrity of the sand mold specimen is also ensured by keeping the binder intact by exposing it only to low temperature range. Comparison of results, tests of statistical significance and subsequent mathematical analysis of heat diffusivity done at 100°C proves the thermal rationale of applying helium to sand molds. A hypothesis stating *"The role of convection as heat transfer mechanism increases in relation to conduction as the helium flow rate is increased"* is postulated and mathematically evaluated using Biot number analysis on two hypothetical helium flow rates of 1 L/min and 4 L/min at 435°C. The analysis supports the presented hypothesis.

## 2) BACKGROUND

Figure 2 presents the temperature distribution during solidification of metal in a sand mold.

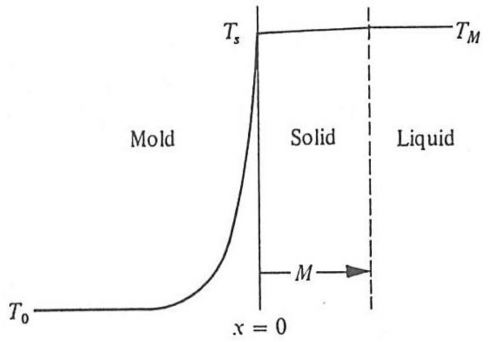


***Figure 2: Temperature Distribution during Solidification of Metal in a Sand Mold (Poirier and Geiger, 1994)***

For a temperature distribution as indicated by Figure 2 the thickness of the metal solidified is given by following equation (Poirier and Geiger, 1994).

$$M = \frac{2}{\sqrt{\pi}} \frac{(\mathrm{T_M} - T_0)}{\rho_s \; \Delta H_s} \sqrt{k_m \, \rho_m \; c_{p_m}} \sqrt{t} \tag{1}$$

Where, $T_M$ is the melt temperature, $T_0$ is the initial temperature, $\rho_s$ is the density of solidifying metal and $\Delta H_s$ is the latent heat of fusion of the metal. From the equation it is evident that for the same characteristics of metal, the thickness solidified "M" at certain time "t" is dependent on mold properties namely thermal conductivity ($k_m$), density ($\rho_m$) and specific heat capacity ($C_{pm}$). The product of these three properties is known as heat diffusivity that represents the ability of the mold to absorb heat at a certain rate (Poirier and Poirier, 1994). The heat transfer properties of mold material are thus an important factor for the rate of heat extraction from the casting being solidified.

Though different types of sands namely silica ($SiO_2$), zircon ($ZrSiO_4$), olivine ($Mg_2SiO_4$), iron silicate ($Fe_2SiO_4$), etc. are available for use as molding material (Kelpakjian, 1995), however silica sand is the most widely used material in sand molds (Kelpakjian, 1995) mainly because it is the least expensive and it has acceptable properties for molding (American Foundrymen's Society, 1965).

Table 1 lists some typical values for the thermal conductivity of materials used to make these insulating molds (Poirier and Poirier, 1994).

*Table 1: Typical Values of Thermal Conductivity of Insulating Molds (Poirier and Poirier, 1994)*

| Mold Material | Thermal Conductivity (W/m K) |
|---|---|
| Silica sand | 0.52 |
| Mullite | 0.38 |
| Plaster | 0.35 |
| Zircon sand | 1.04 |

The thermal conductivity values presented in Table 1 when compared to those of metals that are typically used in permanent molds (see Table 2 (Argyropoulos and Carletti, 2008)), highlight the extent of insulation that sand molds present.

*Table 2: Typical Values of Thermal Conductivity of Conducting Molds (Argyropoulos and Carletti, 2008)*

| Mold material | Thermal Conductivity (W/m K) |
|---|---|
| Copper | 399 |
| Stainless steel | 52 |
| Cast iron | 36 |

In reality, the heat transfer within mold is a complex phenomenon since thermal conductivity of the porous sand mold material is not as simple as *solid* material; on a microscopic level, the heat is transferred by conduction through each particle, conduction & convection in the void within the pores and radiation from particle to particle across the pores (Poirier and Poirier, 1994). Thus the thermal conductivity of the mold material is dependent on number of factors like particle material, particle size, binder, volume fraction of pores, gas in the pores, emissivity of the particles and temperature (Poirier and Poirier, 1994). Keeping all other things constant, the heat transfer through the pores could be improved by employing a higher thermally conductive gas in the pores instead of air.

The result should thus be an improvement in the overall heat transfer properties of bulk sand mold material.

Helium owing to its high thermal conductivity in comparison to air has been successfully used for the purpose of enhancing heat extraction rate in the air gap of the metallic molds to suppress the insulating effects of air in those molds with promising results (Doutre, 1998; Doutre, 2000; Wan and Pehlke, 2004; Argyropoulos and Carletti, 2008; Griffiths, 2008). In these studies, Doutre (1998, 2000) concentrated mainly on the cooling time reductions and productivity aspects by injection of helium in metallic molds whereas other researchers (Wan and Pehlke, 2004; Argyropoulos and Carletti, 2008) primarily targeted the effect of helium on heat transfer aspects. Argyropoulos and Carletti (2008) reported an increase of 48% in the average heat transfer coefficient (from time of casting to the onset of metal-mold separation) by helium injection in metallic molds under special conditions (Argyropoulos and Carletti, 2008). The porous nature of the sand mold presents potential to get them engulfed with helium. Intrigued by the opportunity, some researchers have employed helium to the porous molds with encouraging results (Griffiths, 2008; Saleem, 2011). An average surface finish ($R_a$) of 14.11µm is deduced from the work of Saleem and Makhlouf (2012) for the helium-assisted sand casting processes that is comparable to a surface finish ($R_a$) of 13.99µm reported for baseline (conventional sand casting process) (Saleem and Makhlouf, 2012). As for the economics of the process, an elementary cost analysis done under certain assumptions (Saleem, 2011), shows that enhanced mechanical properties obtained in consequence of refined microstructure (formed due to better cooling rate via helium infusion) is the main facet of the process that can upset the apparent “cost penalty” of applying helium; the analysis shows certain cost factors that are a function of casting weight (Sirinivasan, 2000) to be reduced by up-to 8% for certain conditions of helium-assisted process due to reduced casting weight requirements (because of better properties). The microstructure and properties of the helium-assisted sand cast material have been reported elsewhere (Saleem and Makhlouf, 2012); whereas, the paper presented herein analyzes the effect, helium has on the heat transfer properties of porous sand mold material and postulates the heat transfer mechanism considering continued flow of helium as possible mode of its application to sand molds.

# 3) APPARATUS, MATERIALS AND PROCEDURES

## 3.1) Design of Experiment

A full factorial $2^2$ experiment design with two factors (test environment and specimen temperature) having two levels each i.e. Air and Helium for the test environment and 25°C and 125°C for the temperature was planned for the experimentation in this work. Table 3 shows the design of experiment (DOE).

*Table 3: Design of Experiments*

| Variables | | Performance Measure |
|---|---|---|
| **Factors** | **Levels** | |
| 1) Test Environment<br>2) Specimen Temperature | (Air, Helium)<br>(25°C, 125°C) | Apparent Thermal Conductivity |

## 3.2) Test Specimen

Bonded silica sand specimens in the form of discs were cut from the pre made sand molds. The diameter of each specimen was 45.70 mm and the height was 20 mm. Two holes were drilled at predefined locations for insertion of thermocouples. Figure 3 shows the schematic of the specimen used for experiments whereas Table 4 gives the characteristics of sand mold specimen.

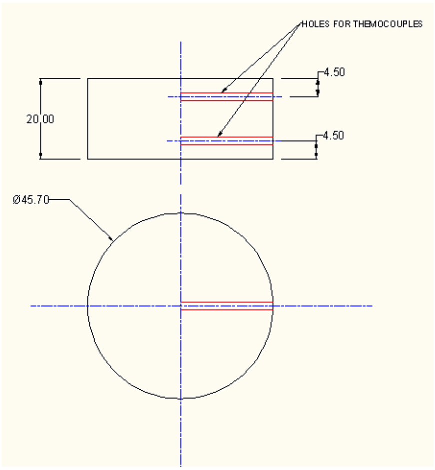


*Figure 3: Schematic of the Specimen used for the Test*

*Table 4: Characteristics of Sand Mold Specimen Tested*

| Sand Type | Resin | AFS Grain Fineness # | Specific Permeability |
|---|---|---|---|
| Silica | Furan Based | 80 | $1.51 \times 10^{-11}$ m$^2$ |

## 3.3) Experimental Setup & Experiment Conditions

Guarded comparative longitudinal heat flow technique (ASTM E1225) (ASTM, 2008) is used herein to measure the apparent thermal conductivity of the sand mold specimens. For measurements in helium environment slight adaptation to the base setup was necessitated to ensure that helium displaces the air from the pores and stays in there; care was though taken that the standard's principle of measurement i.e. unidirectional heat flow along the axis of test stack is not affected. The modified experimental setup employed herein is explained in section 3.3.2

### *3.3.1) Test Stack & Guarded Configuration for Baseline Measurements*

A test stack was developed in light of ASTM standard's guidelines (ASTM, 2008) wherein 2 discs of machineable ceramic[i] with same dimensions and provision for thermocouples as were for the sand specimen to be tested, were used as reference material. The total length of the test stack was thus 60 mm (20 mm for each piece). Commercially available spun ceramic fiber blanket was used to insulate the test stack. The metallic guard employed in the work had wall thickness of 0.125 inch (outer dia 4 inch and inner dia 3.75 inch). Ratio of stack to guard diameter was thus 2.22. An electric heater was used as heat source and ice-water combination was used as the heat sink. Figure 4(a) shows the schematic of configuration used for baseline measurements. Sand mold specimen and the reference material used herein are shown in Figure 5.

### *3.3.2) Test Stack & Guarded Configuration for Measurements in Helium Environment*

For ensuring that helium, when directly admitted to the sand mold specimen stays in its pores, sand mold specimen was completely sealed along with already inserted thermocouples and two protruding pins (tubes) for provision of helium's admission to and exit from the sealed specimen. This sealing was carefully done wherein, for peripheral sealing, a commercially available *thermally insulating* epoxy[ii] was employed, whereas, for sealing the end faces of the specimen, highly *thermally conductive* material (thin copper plates in this case) were used; the arrangement ensured the unidirectional heat flow along the axis of the test stack. Other traits of the test stack and guarded configuration were the same as explained in section 3.3.1 except that in this case, metallic guard was made in two detachable parts to let sealed specimen with protruding pins (tubes) and thermocouple wires to be conveniently positioned inside the guard. Figure 4(b) shows the schematic of configuration used for measurements in helium environment whereas Figure 6 shows the two part guarded configuration used herein.

### *3.3.3) Calibration*

Both the configurations were calibrated using opaque fused quartz[iii] as reference material in the light of standard's guidelines (ASTM, 2008).

### *3.3.4) Approach for Measurements in Helium Environment*

Helium was admitted into the specimen via the supply tube after passing through a flow meter at gauge pressure of 12.5KPa (0.1234 atm. higher than atmospheric pressure) to initially purge the air from the specimen after which an outlet valve purposely provided at downstream of the setup was closed while keeping the flow meter valve at upstream side of the setup open. This was to ensure that under proper sealing conditions of the specimen, flow meter would give a zero value even with flow meter valve open and helium would get trapped inside the pores of the specimen at 0.1234 atm. gauge pressure. Any leakage from the system could thus be detected if a non-zero value on flow meter is obtained with supply valve opened and outlet valve closed.

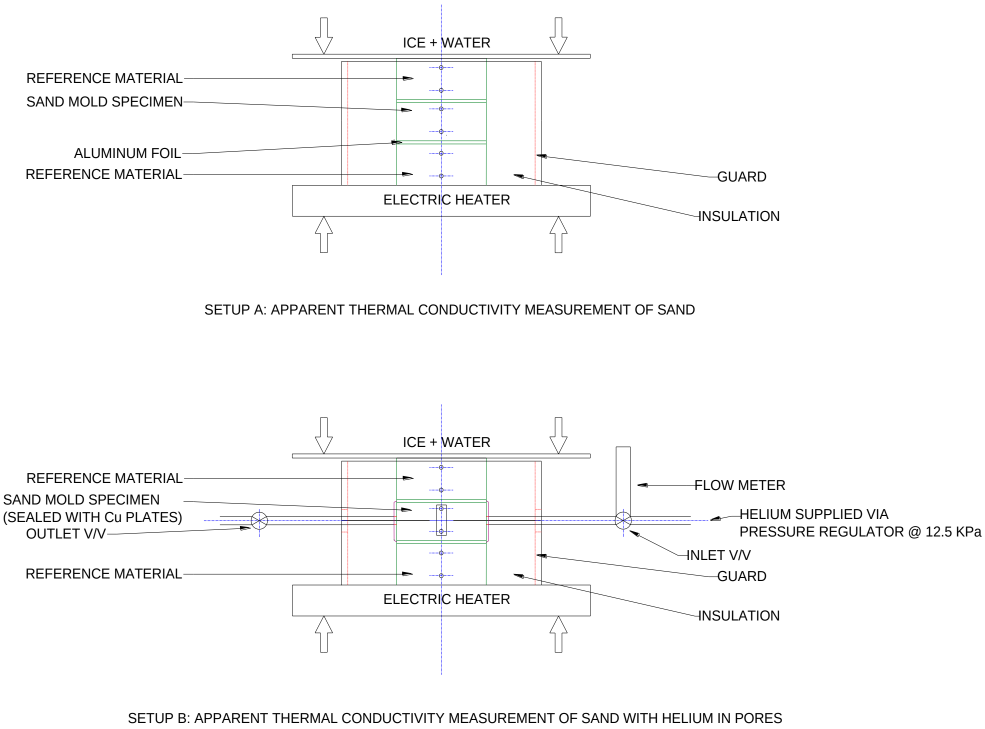


*Figure 4: Schematic of Experimental Setup*

*Figure 5: Sand Specimen and Reference Material used for Experimentation*

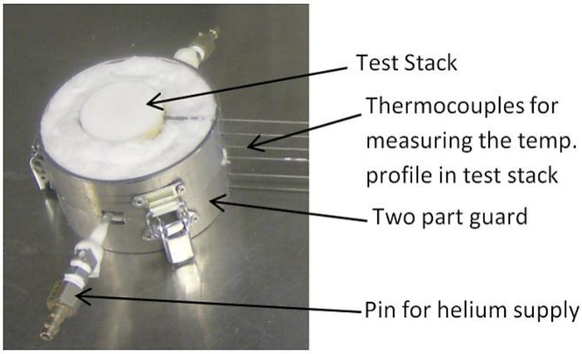


*Figure 6: Two Part Guarded Configuration used for Measurements in Helium Supply*

## 3.5) Data Collection

Electric heater was adjusted and thermocouples were left to record values for an extended period of time so that the average temperature of the specimen was the one desired for measurement and the values were stable enough. Temperature profile developed in the test stack was measured by six K type thermocouples that were interfaced to the data acquisition system[iv]. DasyLab version 5.61.10[v] was used as data acquisition software and data was recorded at sampling rate frequency of 1000 measurements per sec averaged at 100, thus giving a time interval of 0.1 sec between recorded values. The recorded values were exported to Microsoft® Excel® for analysis and the calculated values were averaged over a stable range.

The equation used in this regard is reproduced herein (ASTM, 2008).

$$K_S = \left(\frac{\Delta Z_S}{\Delta T_S}\right) \times \left(\frac{K_R}{2}\right) \times \left(\frac{\Delta T_{R1}}{\Delta Z_{R1}} + \frac{\Delta T_{R2}}{\Delta Z_{R2}}\right) \tag{2}$$

Where, $K_S$ is the unknown apparent thermal conductivity of test specimen, $\Delta Z_S$ is the mutual distance between the thermocouples' position on specimen whose thermal conductivity is being measured. $\Delta T_S$ is the temperature profile developed in the specimen measured at known positions of the thermocouples. $K_R$ is the known thermal conductivity value of the reference materials being used. $\Delta Z_{R1}$ is the mutual distance between the thermocouple's position on reference material (used at the heater end) and $\Delta T_{R1}$ is the temperature profile developed in it where as

$\Delta Z_{R2}$ and $\Delta T_{R2}$ are the corresponding values for reference material used at the heat sink end. (ASTM, 2008)

## 4) RESULTS, ANALYSIS AND DISCUSSION

### 4.1) Thermal Conductivity

Table 5 summarizes the results obtained for all of the test specimens. When measuring in helium environment, third specimen disintegrated, resulting into erroneous thermocouple readings which were discarded. Three values are thus reported for measurements in air environment whereas two are reported for measurements in helium environment.

*Table 5: Results Shown for Each Specimen Tested*

| Test Environment | Spec. Temp. | Apparent Thermal Conductivity (W/m K) | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | Mean |
| Air | 25°C | 0.529 | 0.546 | 0.565 | 0.547 (0.018) |
| | 125°C | 0.478 | 0.495 | 0.496 | 0.490 (0.010) |
| Helium | 25°C | 1.036 | 1.03 | - | 1.033 (0.004) |
| | 125°C | 1.022 | 0.929 | - | 0.976 (0.066) |

*Values in parenthesis show standard deviation

Average value of apparent thermal conductivity for the baseline case i.e. air in the pores is 0.547 W/m K at 25°C and 0.49 W/m K at 125°C. For the helium it is 1.033 W/m K at 25°C and 0.976 W/m K at 125°C. The obtained values measured at corresponding temperatures are in good agreement with each other with a very small standard deviation at each temperature for respective test environment.

The results are subjected to "one way" analysis of variance (ANOVA) to validate the findings by determining the statistical significance of the environment's effect at each temperature (25°C & 125°C). The level of significance is taken to be 0.05. In ANOVA, the total variation observed in the data is broken into accountable sources so as to determine which variation component can be attributed to error and which can be attributed to the effect of factor/group (in this case the environment i.e.

air & helium is the factor/group); this variation is measured in the form of sum of squares "SS" that, for the case of "between groups" value, is calculated as the sum of squared deviations between each group mean and the grand mean multiplied by number of observations, and for the case of "within group" value, it is calculated as the sum of squared deviations between each data point in a group and the mean of that group (Ross, 1995; Berger and Maurer, 2002). Dividing these "sum of squares" values by respective degree of freedom "df" yield variances "MS" that represent the spread of observations about their mean wherein degree of freedom are the number of terms that are free to vary while estimating a parameter from data (Ross, 1995; Berger and Maurer, 2002). The two variances calculated as above are subjected to an "F-test" named after Sir Ronald Fisher for comparison wherein the ratio of these two variances is determined which provides a test statistic value "F" that is then compared with a critical value of F, required to consider two variances to be unequal at a certain confidence level (Ross, 1995; Besterfield et al., 2003). This F-critical is the abscissa value of the F distribution at associated degrees of freedoms, to the right of which area under the curve is equal to the significance level selected (Besterfield et al., 2003). Table 6 & 7 present the results for ANOVA performed herein.

*Table 6: One Way ANOVA at 25°C*

| **Source of Variation** | **SS** | **df** | **MS** | **F** | **P-value** | **F-critical** |
|---|---|---|---|---|---|---|
| Between Groups (Helium & Air) | 0.283824 | 1 | 0.283824 | 1277.21 | 4.82 E-05 | 10.128 |
| Within Groups | 0.000667 | 3 | 0.000222 | | | |
| **Total** | **0.284491** | **4** | | | | |

*Table 7: One Way ANOVA at 125°C*

| **Source of Variation** | **SS** | **df** | **MS** | **F** | **P-value** | **F-critical** |
|---|---|---|---|---|---|---|
| Between Groups (Helium & Air) | 0.28324 | 1 | 0.28324 | 187.61 | 0.000842 | 10.128 |
| Within Groups | 0.004529 | 3 | 0.00151 | | | |
| **Total** | **0.28777** | **4** | | | | |

Considering that P-value represents the smallest significance level for which null hypothesis is rejected (Pal and Sarkar, 2008), since at both the temperatures, the P-value is less than the selected significance level of 0.05, thus there exists significant difference in the values obtained in two different environments i.e. hypothesis of no difference (null hypothesis) doesn't hold true. Figure 7 shows the graphical summary of the results.

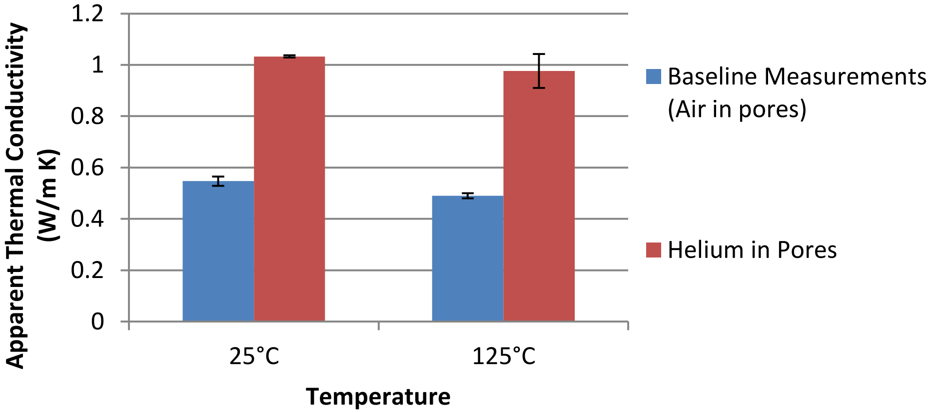


*Figure 7: Results of Apparent Thermal Conductivity Experiment*

The pattern of the curves rules out any role of interactions between the variables and it is therefore concluded that a marked increase in the level of the apparent thermal conductivity of sand is obtained when readings were taken with helium in the pores opposed of air.

The benefit is expected to continue at higher temperatures as well, considering that the thermal conductivity of helium remains higher than that of air at elevated temperatures also (Poirier and Geiger, 1994).

## 4.2) Heat Diffusivity

The heat diffusivity of the molding material (sand in this case) is given by the following equation (Poirier and Poirier, 1994),

$$Heat\ Diffusivity = \kappa\rho C_p \tag{3}$$

The product represents the ability of the mold to absorb heat at a certain rate (Poirier and Poirier, 1994). To simulate the effect of helium on heat diffusivity, calculations are done by taking dataset presented in Table 8, whereas the value of K is interpolated at 100°C from the measurements presented in section 4.1.

*Table 8: Dataset used for Calculations*

| | **Helium**[vi][vii] | **Air**[viii][ix] | **Sand**[x][xi] |
|---|---|---|---|
| $C_p$ (KJ/Kg K) | 5.193 | 1.011 | 0.830 |
| ρ (g/cc) | $14.685\text{x}10^{-5}$ | $95\text{x}10^{-5}$ | 1.649 |

Plugging in the values in equation; heat diffusivity at 100°C comes out as 0.626 $\frac{(\frac{KJ}{m^2K})^2}{sec}$ in the case of conventional sand mold where as it rises to approximately 1.215 $\frac{(\frac{KJ}{m^2K})^2}{sec}$ in the case of helium in the pores. This corresponds to ~94% increase than the conventional sand mold specimen.

As can be seen from the presented results, the heat transfer properties of the sand molds can be improved using helium; however it would take away from the potential benefits unless the findings are discussed in the context of operational aspects of the sand casting process. A critical facet in this regard is that how helium could be actually administered to the sand molds during the course of the process and the resulting influence on the heat transfer mechanisms. In this regard following two possible scenarios are discussed herein,

*i) Establishment of a controlled environment with stagnant helium in the pores and the cavity, similar to when air is normally existent in the conventional sand casting process.*

*ii) Supplying helium continually during the course of the process.*

The first scenario represents the case wherein the existent heat transfer mechanism of the conventional sand casting process should not effectively change as air is simply replaced by helium (just another medium with superior thermal properties) for faster heat extraction. However, producing such an arrangement would be operationally complex considering the imposed process constraints like, a requirement of provision for introduction of molten metal into the sand mold and escape of the binder gases generated during the process. In fact, helium is reported to be resulting into more generation of binder gases in an enclosed chamber when applied to the resin bonded molds (Griffiths, 2008), thereby making the escape provision even more critical and maintaining such stringent requirements of an enclosed environment would require much effort on a shop floor.

The second scenario presents an alternate and possibly more straightforward approach of practically applying helium to the sand molds on a shop floor. It involves administering helium *continually* to the sand molds during the course of the process without the need to *lock* it in the pores. This should simplify the operational issues of pouring of metal and escape of process generated gases. The possible arrangements for such an approach have been reported elsewhere (Saleem and Makhlouf, 2012) and is not the scope of this particular paper however realization of helium's this possible mode of application is important for understanding the heat transfer mechanism involved. This continuous supply mode, would introduce an aspect of forced convection bettering the benefits in addition to the already enhanced thermal properties of mold material achieved by mere presence of helium in the pores; therefore helium flow rate would form an additional process parameter; a higher flow rate would make convection in the cavity a dominant mode for heat removal in relation to conduction through the mold. Figure 8 shows the visualization of the flow pattern of helium through the sand mold in the continuous supply mode parallel to a solidifying plate in the cavity.

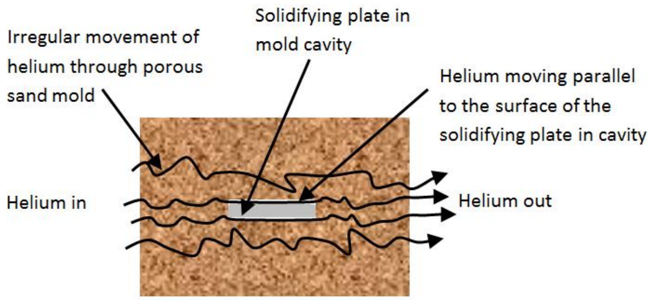


*Figure 8: Visualization of Flow Pattern of Helium in the Continuous Mode of Supply*

For this case a hypothesis regarding the heat transfer mechanism stating *"The role of convection as heat transfer mechanism increases in relation to conduction as the helium flow rate is increased"* can be postulated herein for such a scenario supported by a simple mathematical analysis involving Biot number (Bi) computation wherein relative contribution of convection (in the gap) to conductance (in the mold) is evaluated. Biot number is a dimensionless parameter that relates the heat transfer resistance inside the body (resistance to conductive mode of heat transfer) with heat transfer resistance at the surface of the body (resistance to convective mode of heat transfer) (Kreith and Bohn, 2001). Equation (4) gives the relation for Biot number (Kreith and Bohn, 2001).

$$Bi = \frac{Conduction\ thermal\ resistance}{Convection\ resistane} = \frac{(\frac{L}{k})}{(\frac{1}{h})} = \frac{hL}{k} \quad (4)$$

Where "h" is the convective heat transfer coefficient through the fluid (helium in this case), "L" is the characteristic length and "k" is the thermal conductivity of the body (sand mold in this case). A smaller value of Biot number would indicate lesser contribution of "convection" as heat transfer mechanism whereas a higher value of it would indicate more contribution of "convection" as a heat transfer mechanism i.e. less resistance to convective mode of heat transfer. For the case at hand, as shown in Figure 8, helium would be flowing from one side of the mold to the other through pores of the mold. In its path it would encounter the cavity with solidifying metal plate wherein helium would then flow along the surface of the solidifying metal in a small gap between surface of solidifying metal and the mold. The details pertaining to the calculations of the parameter are given in Appendix-A. The analysis indicates that as the flow rate increases, the relative contribution of convection in the cavity increases in comparison to the conduction in the mold, as is evident by Biot number, which, for a flow rate of 1 L/min is determined to be 3.06 and further rises to 6.14 for a flow rate of 4 L/min thus establishing the role of helium flow rate as a new process parameter in helium administered sand casting process.

## 5) CONCLUSIONS

Following conclusions are drawn from the work presented herein:

- Presence of helium inside the pores of sand mold specimen increases its heat transfer properties namely apparent thermal conductivity and heat diffusivity; the value of apparent thermal conductivity of sand mold specimen increases ~89% at 25°C and ~99% at 125°C with helium inside the pores as compared to the baseline (without helium) whereas heat diffusivity is shown to increase ~94% at 100°C in comparison to baseline (without helium).

- Flow rate of helium is propounded to be a new process parameter in case of helium-assisted sand casting process with convection also playing its part in the heat transfer mechanism.

The findings are supported by statistical tests of significance and mathematical analyses.

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## APPENDIX-A

A simplified 2D analysis is done herein for an 8″ plate section solidifying in a sand mold with an assumed cavity gap “δ” of 0.1″ (between plate and mold); a case of fluid (helium) flowing between parallel plates (one plate being the mold surface and the other one being the surface of the metal that is being solidified in the cavity) is considered. Figure A-1 shows the schematic of this arrangement.

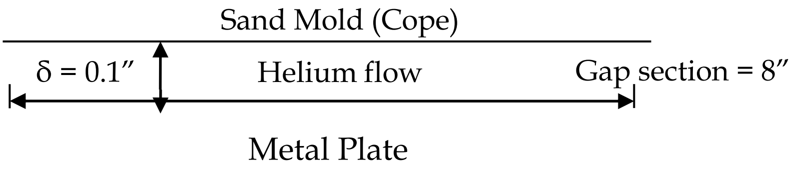


*Figure A-1: Schematic of the Sand Mold and Gap*

Table A-1 and A-2 show the assumptions made and data set used respectively

*Table A-1: Assumptions for Mathematical Analysis*

| | |
|---|---|
| Metal Temp. | 850°C |
| Mold Temp. | 20°C |
| Gap Height | 0.1″ |
| Gap Section | 8″ |
| Mold Height[xii] | 6″ |

*Table A-2: Dataset Used for Mathematical Analysis*

| Properties[vi] of helium at 435°C and 1 atm. pressure[xiii] | Properties of sand mold[xiv] |
|---|---|
| $\mu = 3.629 \times 10^{-5}$ Pa-sec (kg/m-sec)<br>$\rho = 0.069$ kg/m$^3$<br>k = 0.283 W/m K | K = 1.033 W/m K |

The value of "h" to be used in equation (4) is computed by first estimating the Reynolds number (a dimensionless parameter whose value determines the flow to be either laminar or turbulent for the case of forced convection) using following equation (Mills, 1995).

$$Re_{D_h} = \frac{(\frac{m^0}{A_c})D_h}{\mu}$$

Where $D_h$ is the so called hydraulic diameter in meters, $m^0$ is flow rate in kg/sec, $A_c$ is the area of the gap in $m^2$ and $\mu$ is the dynamic viscosity in kg/m-sec. With a $D_h$ of $5.03 \times 10^{-3}$ m and $A_c$ $5.16 \times 10^{-4}$ $m^2$(calculated for the gap dimensions considered herein), the Reynolds number comes out to be 0.31 and 1.24 for the flow rates of 1 L/min ($1.15 \times 10^{-6}$ kg/sec) and 4 L/min ($0.46 \times 10^{-5}$ kg/sec) respectively. Since these values are less than 2300 so a laminar flow is encountered for which a Nusselt number using following equation (Poirier and Poirier, 1994; Kreith and Bohn, 2001) can be used (taking Pr =1.0).

$$Nu = 0.664 Re^{0.5} Pr^{0.333}$$

An alternate relation for Nusselt number is $hD_h/k_f$ where $k_f$ is the thermal conductivity of fluid (opposed to solid body's thermal conductivity used in equation 4) (Poirier and Poirier, 1994; Kreith and Bohn, 2001). The "h" thus computed from this equation can be used to determine the Biot number using equation 4. Table A-3 shows the results of the analysis.

*Table A-3: Results of Mathematical Analysis (Role of Convection in the Mold Cavity to Conduction through Mold Material)*

| Flow Rate | Bi |
|---|---|
| 1 L/min (1.15 x $10^{-6}$ kg/sec) | 3.06 |
| 4 L/min (0.46 x $10^{-5}$ kg/sec) | 6.14 |

The analysis indicates that as the flow rate increases, the relative contribution of convection in the cavity increases in comparison to the conduction in the mold, as is evident by Biot number that rises from 3.06 for a flow rate of 1 L/min to 6.14 for a flow rate of 4 L/min.

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[i]MACOR®, Corning Incorporated Lighting & Materials
Houghton Park CB-08, Corning, NY 14831, USA.
[ii]Durapot 866®, Cotronics Corp. 131 47th Street, Brooklyn, NY 11232, USA.
[iii]Technical Glass Products, 881 Callendar Blvd., Painesville Twp. OH 44077, USA.
[iv]National Instruments Corporation, 11500 N Mopac Expwy, Austin, TX 78759, USA.
[v]Measurement Computing Corporation, 10 Commerce Way, Norton, MA 02766, USA.
[vi]National Institute of Standards & Technology (NIST), (http://webbook.nist.gov/chemistry/fluid/), Accessed August 29, 2014.
[vii]Values for helium taken at 100°C (373K) and supply pressure of 12.5KPa (gauge) (1.1234 atm. absolute).
[viii]Fluid Properties Calculator, (http://www.mhtl.uwaterloo.ca/old/onlinetools/airprop/airprop.html), Accessed August 29, 2014.
[ix]Values of air are taken at 100°C, atm. pressure.
[x]The Engineering Toolbox, (http://www.engineeringtoolbox.com/specific-heat-capacity-d_391.html), Accessed August 29, 2014.
[xi]$C_p$ value taken for analysis was for the quartz sand whereas ρ& volume fraction of sand are measured from Archimedes principle; volume fraction = 0.8968.
[xii]Height of cope for an available sand mold used at ACRC (Advanced Casting Research Center, WPI, Worcester MA 01609, USA) for casting an 8″ plate.
[xiii]435°C is the average temp. of mold and metal temps. taken herein.
[xiv]Value of thermal conductivity measured with helium inside the pores at 25°C (Table 5).