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Design and Fabrication of Cooling Slope System

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ABSTRACT

Currently, the usual methods available for large scale production of semisolid slurry are mechanical stirring, electromagnetic stirring, etc. These suffer from drawbacks like complex design, high cost, structural inhomogeneity and low efficiency. The cooling slope is considered to be a simple but effective method because of its simple design and easy control of process parameters, low equipment and running costs, high production efficiency and reduced inhomogeneity. With this perspective, the primary objective of the present research is to design and fabricate a cooling slope setup for experimental investigations of slurry and cast billets. In most casting applications, dendritic microstructure morphology is not desired because it leads to poor mechanical properties. Forced convection is one of the means to suppress these dendrites which flow away to form slurry. This slurry, consisting of rosette or globular particles, provides less resistance to flow even at a high solid fraction and can easily fill the die-cavity. The stated principle is the basis of a new manufacturing technology called "semi-solid forming" (SSF), in which metal alloys are cast in the semi-solid state. This technique has numerous advantages over other existing commercial casting processes, such as reduction of macrosegregation, reduction of porosity and low forming efforts.
Keywords: Design, Development, Cooling Slope, Method.

I. INTRODUCTION

The mechanical stirrer is not suitable mainly because of unwarranted reaction between the impeller and the corrosive liquid metal, and entrapment of gases during agitation. Similarly, the usage of electromagnetic stirrer for SSF applications has its own drawbacks, because it is generally more energy intensive and technologically complex, leading to higher capital and running costs. Hence, there is a need for a cost effective and simple method of slurry production, and the cooling slope technique introduced in the present research work is most viable method for future commercialization. The cooling slope method of semisolid slurry preparation exhibits many advantages over the other methods. Its advantages are:

(a) It is simple but effective method of slurry production
(b) There is low equipment and running costs
(c) high production efficiency
(d) reduced inhomogeneity

In view of the above, a systematic design and development of a cooling slope, taking account of the effects of initial melt superheat, slope angle, slope length, and slope cooling rate, is required. The most important feature of the current research work is a demonstration of the experimental arrangement of metal mould casting experiments using the cooling slope for liquid aluminum alloy, and appropriate instrumentation to realize this procedure. It also illustrates the process variables affecting the final properties of slurry and the cast semisolid billets.

II. DESCRIPTION OF PHYSICAL PROCESS

As depicted in the schematic in figure 1, the molten alloy from a tundish with an initial superheat is poured on a cooling slope which is cooled from bottom by counter flowing water. The temperatures of molten alloy at different locations of cooling slope starting from slope inlet to slope exit are measured experimentally with K-type thermocouples mounted at different locations of cooling slope.

As already stated, in the solidification process used in the present study, a cylindrical stainless steel mould is considered for production of a cast billet. The cylindrical stainless steel mould is water cooled and is used to cool the liquid metal by extracting heat from the molten alloy. The top surface of the mould is open to atmosphere while the bottom surface is closed by an adiabatic ceramic plate. In the current study, molten A356 aluminum alloy (which is commonly used for casting applications) is preferred for solidification processing with a cooling slope. The initial temperatures of the alloy are predefined.

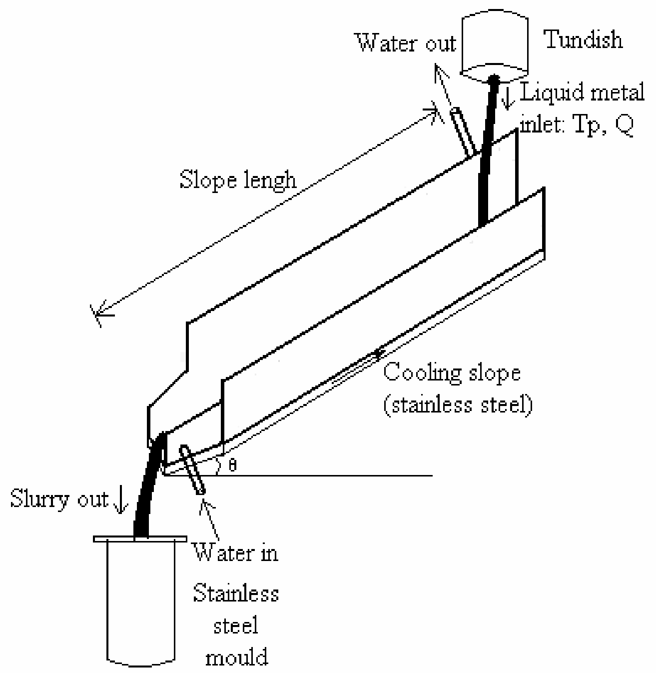


Figure 1: Schematic sketch of cooling slope system

III. PROCESS PARAMETERS

The development of a cooling slope setup in line with the stated method of semisolid production process is derived from the rheological properties of the semisolid slurry which are influenced by fraction of solid, shear rate, and cooling rate throughout the alloy processing. For that reason, the key process parameters in the present practice of semisolid slurry preparation are, initial melt superheat, slope angle, slope length, and slope cooling rate, explained in details as follows.

The enhancement of flow complexity of semisolid slurry during the alloy processing is due to distinct behavior of semisolid slurry viscosity compared to that of pure liquid. The effective viscosity of the semisolid slurry is influenced by numerous process parameters. In actual practice, the slurry viscosity is a function of solid fraction and shear rate apart from other key influencing factors.

A. Melt Superheat

It is well understood that the initial melt superheat during semisolid slurry production is an important factor affecting the microstructure of the final cast products. Pouring temperature will affect the fluidity of the melt which, in turn, will affect the shear rate, exit solid fraction, macrosegregation extent and slurry particle size distribution.

B. Slope Angle

Slope angle directly affects the driving force for the forced convection under gravity. With other parameters remaining constant, higher slope angle will imply faster melt flow (high shear rate) but less residence time for solidification. It will be interesting to see how the final microstructure is affected.

C. Slope Length

Slope length will directly affect the residence time for solidification. For instance, longer slope will imply more solidification and cooler slurry exit. How this would affect the rheological properties and final microstructure would be a subject of study in this work.

D. Slope Cooling Rate

It is observed that slope cooling rate during semisolid slurry production is also a key variable affecting the microstructure morphology of the final cast products. In the current research investigations, the slope is cooled with different cooling heat fluxes (such as relatively lower, moderate, and higher heat fluxes corresponding to relatively lower, moderate, and higher water flow rate underneath the slope, respectively) with the purpose of examining the effect of cooling rate on the final slurry properties and microstructure.

IV. DESIGN AND DEVELOPMENT OF COOLING SLOPE SETUP

The cooling slope is designed to cast cylindrical billets, which falls in the range of billet diameters normally used in die casting machines for semisolid forming. Figure 2 shows the details of the cooling slope, and figure 3 shows the disassembled components of the cooling slope used for experiments. The cooling slope mould assembly consists of several components such as a thin rectangular water channel underneath the slope (thin rectangular channel in between cooling slope top and bottom assembly), arrangement for tilting the slope (tilting flange and locking pin assembly) and vertical cooling slope stand in combination with horizontal dovetail.

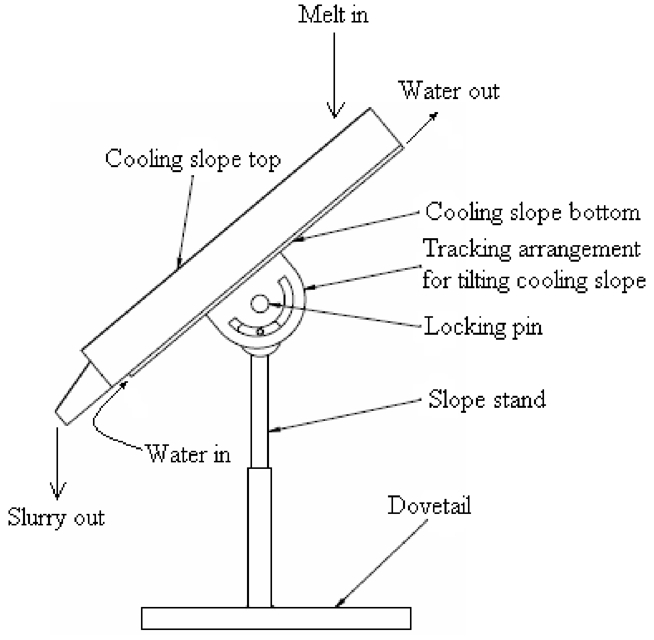
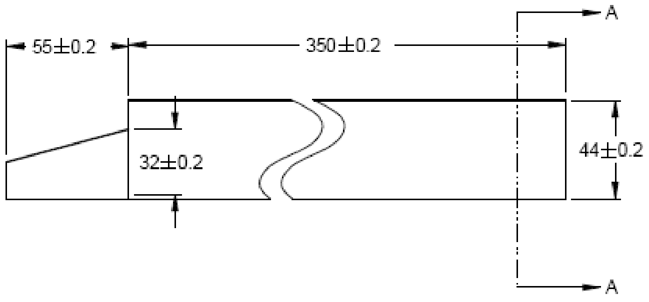
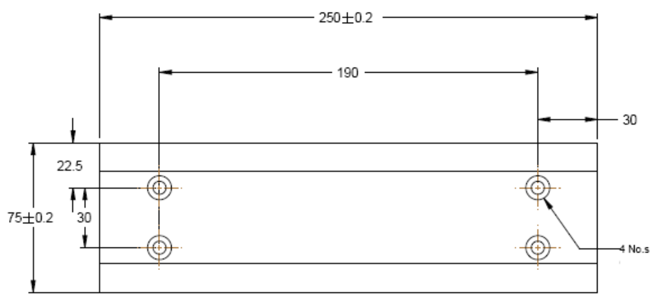


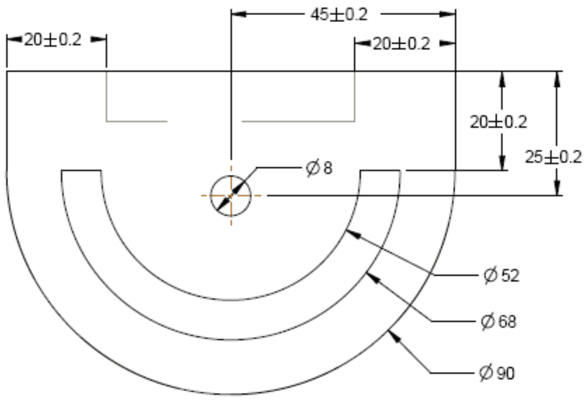
Figure 2 : Details of cooling slope



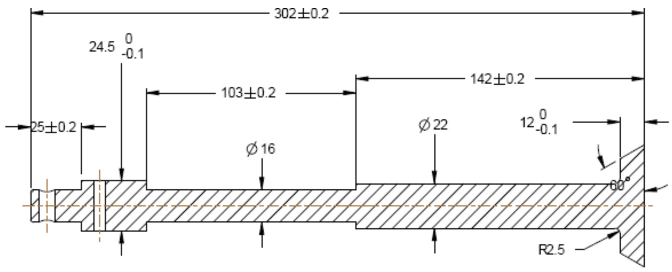
(a) Cooling slope top



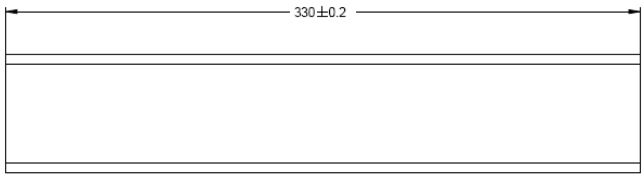
(b) Cooling slope bottom



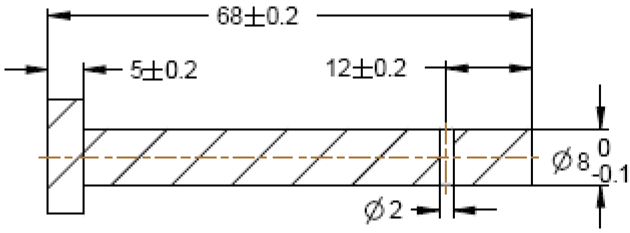
(c) Tilting flange



(d) Slope stand



(e) Dovetail



(f) Locking pin

Figure 3 : Components of cooling slope

The top surface of cooling slope is the zone of active shearing wherein the gravity together with tilt and melt flow inertia shears off the molten metal. The bottom surface of cooling slope is the zone of active cooling of molten metal for realizing high cooling rates. It is cooled externally and indirectly, in turn, extracting heat from molten metal by maintaining flow of water in a counter flow direction.. This arrangement will allow active control of cooling of the metal from the bottom of the cooling slope. Since the high temperature molten aluminum comes in direct contact with the top part of cooling slope surface, the material for the top part of cooling slope should have high thermal shock resistance together with high melting point and high thermal conductivity. In addition, the material should be non-wetting to liquid aluminum. Similarly, the bottom part of cooling slope should have excellent corrosion resistance since it is exposed to water flow. Among the engineering materials available, stainless steel is the most suitable option for both top and bottom parts of cooling slope for such an application. Molten aluminum is highly reactive. It can react with the steel surface of the cooling slope to form intermetallic compounds. To prevent this, the outer surface of the cooling slope that comes in contact with molten metal is given an anticorrosive coating of boron nitride of about 100 microns thickness. Additionally, the boron nitride coating prevents the metal from sticking to the steel surface. Ideally, cooling slope design should be such that effective partial solidification of molten metal should occur at the slope wall with formation of columnar dendrites which are fragmented under the action of shearing.

The tilting arrangement for cooling slope consists of a tilting flange and locking pin assembly. It enables the cooling slope to tilt within a range of 0-90° with respect to the horizontal plane by means of a slightly tapered locking pin (to aid easy removal and insertion). The tilting flange and locking pin assembly are also made of stainless steel.

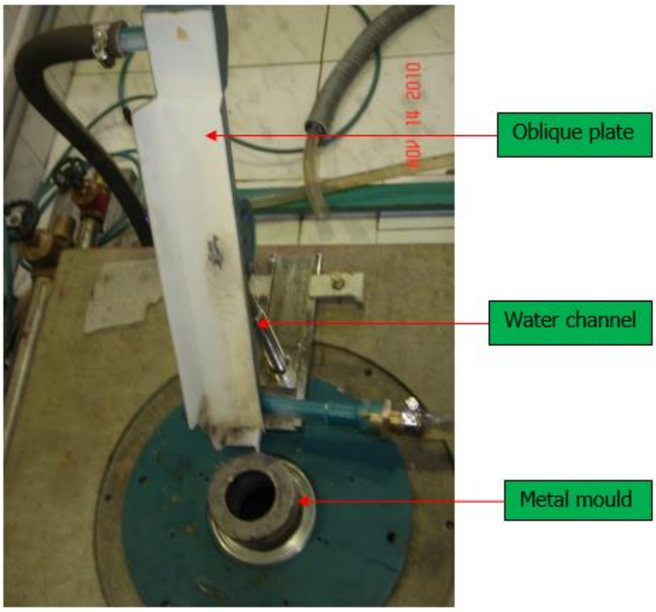


Figure 4 shows an exploded photograph of the cooling slope used in the experiments. The inlet of the coolant water is near the bottom end of cooling slope. In this case of water as coolant, the flow is against the action of gravity towards the outlet which is at the top of slope. This arrangement ensures that there is no static pressure build-up and that the flow is in the direction opposite to natural potential gradient. The stated arrangement is made leak proof and will prevent ingress of water into the molten metal flow path.

V. THERMAL ASPECTS OF DESIGN AND ANALYSIS OF COOLING SLOPE

The molten alloy, as it flows down the cooling slope, undergoes partial solidification as it losses heat to the counter flowing water through the slope wall and also to the air film in the surrounding. In other words,

Heat lost by liquid alloy ($\dot{Q}_{alloy}$) = Heat gained by water through slope wall ($\dot{Q}_{water}$)+ Heat gained by air film surrounding liquid alloy ($\dot{Q}_{air}$)

Heat lost by liquid metal alloy ($\dot{Q}_{alloy}$)= Sensible heat lost by liquid metal alloy($\dot{Q}_{alloy,sensible}$) + Latent heat lost by liquid metal alloy($\dot{Q}_{alloy,latent}$)

$$\dot{Q}_{alloy,sensible} = \dot{m}_{alloy}\, c_{p,alloy}\, (T_{alloy,pouring} - T_{alloy,exit}) \quad (1)$$

$$\dot{Q}_{alloy,latent} = \dot{m}_{alloy}\, f_s \mathcal{L} \quad (2)$$

$$\dot{Q}_{water} = \dot{m}_w\, c_{pw}\, (T_{wo} - T_{wi}) \quad (3)$$

$$\dot{Q}_{air} = \dot{Q}_{mixed\ convection} + \dot{Q}_{radiation} \quad (4)$$

$$\dot{Q}_{mixed\ convection} = h_{mix\ conv}\, A\, (T_{avg.\ alloy} - T_\infty) \quad (5)$$

$$Q_{radiation} = A\, \sigma\, \varepsilon\, (T^4_{avg.\ alloy} - T^4_\infty)$$

$$= h_{rad}\, A\, (T_{avg.\ alloy} - T_\infty) \quad (6)$$

where,

$$h_{rad} = \sigma\, \varepsilon\, (T_{avg.\ alloy} + T_\infty)(T^2_{avg.\ alloy} + T^2_\infty) \quad (7)$$

$h_{mix\ conv}$ can be calculated from the Nusselt number correlation for mixed convection of air over an oblique plate as follows.

$$Nu_{combined} = (Nu^n_{forced} \pm Nu^n_{natural})^{1/n} \quad (8)$$

where, $n = 3$, for vertical and oblique plates, but $n = 3$ *to 4*, for horizontal plates

+*ve* sign for assisted flow (in the present case)

-*ve* sign for opposing flow

and, $Nu_{forced} = 0.664\, Re_L^{0.5}\, Pr^{1/3}$ (9)

$$Nu_{natural} = 0.59\,(Gr_L\ \mathrm{Pr})^{1/4} \quad (10)$$

for, $$Gr_L = \frac{g\beta \sin\theta (T_{avg.\ alloy} - T_\infty)L^3}{\nu^2} \quad (11)$$

$$Re_L = \frac{UL}{\nu} \quad (12)$$

It may be noted here that both natural and forced convection modes are equally important if $\frac{Gr_L}{Re_L^2} \sim 1$. In other words if the value of $\frac{Gr_L}{Re_L^2}$ is in between 0.1 to 10.

In other words $\dot{Q}_{air}$ can be written as

$$\dot{Q}_{air} = (h_{mix\ conv} + h_{rad})\,A\,(T_{avg.\ alloy} - T_\infty) \quad (13)$$

In another way, $\dot{Q}_{water}$ can also be expressed as

$$\dot{Q}_{water} = UA\Delta T_{LMTD} = UA[(\Delta T_i - \Delta T_e)/\ln(\Delta T_i/\Delta T_e)] \quad (14)$$

Overall heat transfer coefficient (U) is expressed as

$$U = \dot{Q}_{water}/(A\Delta T_{LMTD}) \approx \dot{Q}_{alloy}/(A\Delta T_{LMTD}) \quad (15)$$

since heat lost to air is negligible compared to heat absorbed by water i.e. $\dot{Q}_{air} \ll \dot{Q}_{water}$.

In another way, *U* can also be expressed as

$$(1/U) = (1/h_{water}) + (x_{cs}/k_{cs}) + (1/h_{alloy}) \quad (16)$$

where, h_{water} *and* h_{alloy} are the water and alloy sides heat transfer coefficients, respectively; x_{cs} *and* k_{cs} are thickness and thermal conductivity of cooling slope material, respectively.

As the molten alloy is at an elevated temperature, some amount of heat needs to be dissipated in order to form semisolid slurry. Such heat loads cannot be handled by air cooling techniques, unless the slope length is adequate. Hence, from the point of view of compactness and operational ease of the equipment, a water cooling system is implemented in the present design. The whole cooling slope assembly basically acts as a counter flow heat exchanger with water and molten alloy as cold and hot fluids, respectively. Its design allows control of the solidification rate such that semisolid slurry with desired properties can be produced. Further, the thermal design must ensure appropriate cooling range of the molten metal alloy to obtain semisolid slurry at a desired temperature range at the slope exit. Accordingly, forced convection cooling through the thin rectangular channel beneath the cooling slope surface is chosen to achieve these operational conditions.

Stainless steel is chosen as the cooling slope material because of its high melting point and good thermo-structural integrity in the operating range of temperature. The thickness of cooling slope is chosen such that either with or without water cooling it can serve the purpose without excessive temperature rise. Based on these features, a wall thickness of 2 mm is chosen for the cooling slope and also water channel thickness is chosen as 2 mm. To prevent the sticking of the melt to the surface of the cooling slope boron nitride coating (which acts like a good conductor of heat) is provided on the top surface of the cooling slope.

The underneath of the cooling slope is cooled by water at a mean water temperature of about 25°C at the inlet of the cooling slope. This arrangement is found to give a heat transfer coefficient in the range 1000-3000 W/m^2-K with a modest water temperature rise in the range of 3-5°C up to a water flow rate of 15 lit/min for the cooling length range of 200-300 mm. A photograph of the cooling slope assembly at an angle of 60° with respect to the horizontal plane is shown in figure 3.6.

For the base case study with melt pouring temperature of 625°C and cooling length of 250 mm, the corresponding heat transfer coefficient is about 2000 W/m^2-K, and the water temperature rise is about 5°C for a water flow rate of 7.5 litres/min. This results in radiation and mixed convection (both natural and forced together) heat transfer coefficients of 5 W/m^2-K and 40 W/m^2-K respectively, to the hot air film surrounding the molten alloy while flowing down the cooling slope.

The base case process parameters chosen to produce semisolid slurry with desired properties for casting billets with preferred microstructure morphology are also determined with the help of a base case computational model and correspondingly, with a series of rigorous experiments after fabrication of the entire cooling slope setup.

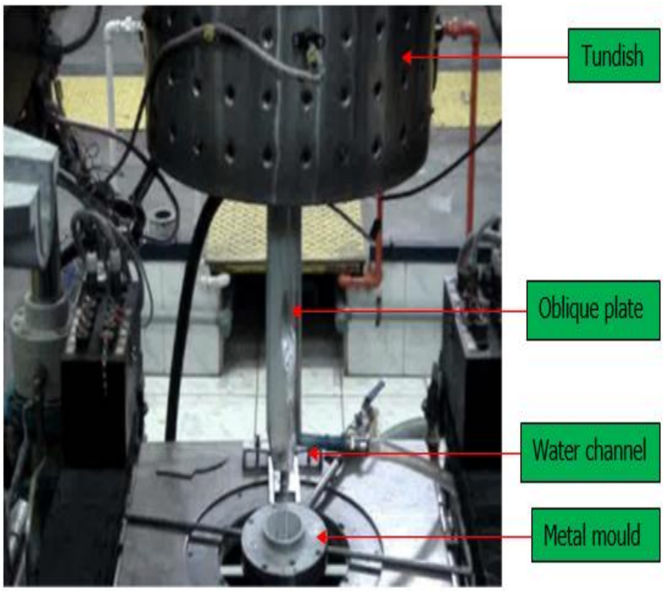


Figure 5 : Photograph of cooling slope assembly

VI. SAFETY PRECAUTIONS

In view of the fact that exceedingly high temperature is associated with cooling slope experiments, enough safety measures have to be taken in all steps, mainly while designing the setup. It is quite obvious that direct contact between liquid aluminum alloy and water is dreadfully hazardous which can cause severe explosions. Hence, utmost safety precautions are followed to make sure that water supply to the cooling slope along with metal mould is leak proof and the adjoining area to experimental setup is entirely dried out.

The additional key safety aspects that are taken into consideration, and are incorporated in the design, are mentioned as follows:

(a) Comprehensive care to avoid direct contact of molten metal with water.

(b) Leak proof cooling system to avoid molten alloy explosion.

The primary feature has been accounted for with the fundamental design of the cooling slope, by ascertaining that there is no spill out or overflow of molten alloy from sides of the slope surface. This is accomplished all the way through making open type rectangular channel-shaped cooling slope surface.

The leak proof coolant water circulation system is designed with proper safety features in the form of rigid and thin water channel underneath the cooling slope.

Besides the stated precautionary measures, the tube assembling the thermocouples is preheated up to about 200°C by means of a gas burner to remove trapped moisture before it is mounted on the cooling slope. In addition, protective aluminized aprons, shoes, safety glasses, hand gloves and helmets are also used by the technical personnel while conducting experiments with molten aluminum.

VII. CONCLUSION

A comprehensive detail about the basic design, constructional features and description of a cooling slope for molten alloys leading to the development of suitable cooling slope system is presented, and the various components of cooling slope geometry are illustrated. A simplified analysis of a cooling slope for solidification process based on a counter flow heat exchanger approach of the cooling slope for liquid aluminum alloy and the associated thermal design issues are presented. The experimental cooling slope system also considers the effects of process variables on the final properties of slurry and the cast semisolid billets. In other words, this also includes a description of the schematic of the experimental setup for melt preparation. The safety precautions followed in the experimental designs, trials and practices are also highlighted. As a whole, the present research work demonstrates the experimental arrangement and procedures for metal mould casting experiments using the cooling slope for liquid aluminum alloy and appropriate instrumentation to realize this practice.

VIII. REFERENCES

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