Spray Cooling Results of Air/Mist Spray Nozzles with Reduced Air Volumes

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Abstract

Continuous casters may benefit with reduced operating costs by decreasing air volumes required for air/mist spray nozzles in secondary cooling zones. Experimental results were examined to determine how heat transfer characteristics were affected by reductions of up to 25% of the air while water volumes were held constant. Mixing efficiencies of air and water were design variables considered. Minimum heat flux and Leidenfrost temperature values were compared at similar water flux density conditions.

Introduction

Recent developments in nozzle design resulted in the introduction of a new air / mist CasterJet spray nozzle. Various changes were made to the internal geometry of the nozzle body, which resulted in improved mixing of the air and water in this chamber. One result of these changes was the reduction in the amount of air required to atomize a specific volume of water, Figures 1 and 2. The benefits for steel mills with air / mist continuous casters include reduced costs as a result of the substantial volumes of air that are not required with these new nozzles.

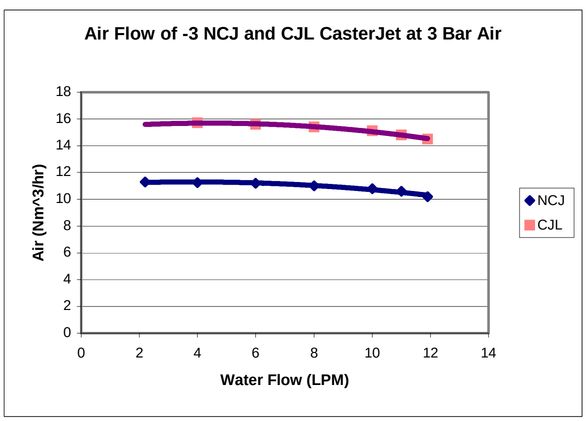

Figure 1: Setup 3

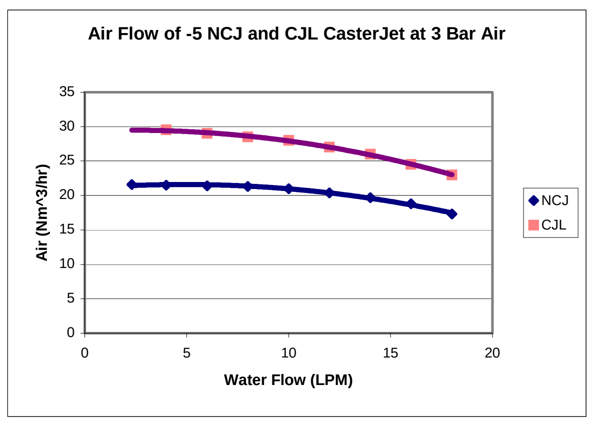

Figure 2: Setup 5

Previous studies have examined the relationships that influence how spray cooling removes heat from continuous casters. Water that is sprayed onto the steel surface above a particular temperature produces a thin layer of steam between the steel surface and the water. This condition is often referred to as "film boiling". Studies that have used hydraulic spray nozzles suggest that the heat transfer coefficient is largely dependent on the mass water flux generated by the spray nozzle. However, the addition of air to the spray creates a more complex problem to analyze. The air provides additional atomization of the water, which aids in the cooling of a steel surface. Since the volume of air used in the new design CasterJet was reduced, the cooling effect of the spray was examined to determine if the heat transfer characteristics were similar.

The change in the nozzle design provided an opportunity to examine the effect of air volume on a number of measurements that are of interest to those concerned with continuous casting thermal characteristics. Literature is plentiful that considered the dynamics of small volumes of water impinging upon heated surfaces. However, the effect of water sprays through nozzles commonly used for industrial purposes is somewhat limited. Those studies reviewed for water sprays typically found that volumetric flux, or the water density, was the most important factor in determining the Leidenfrost point [1]. This value is important for the cooling considerations for continuous casting as it generally defines the point above which relatively constant surface heat transfer occurs. The cooling process above this point is therefore predictable and generally stable. At these high temperatures film boiling produces a vapor barrier that exists between the metal surface and the contact point of the water spray [2]. An air / mist spray nozzle is a rather complex mechanism that emits a water spray and has become common for secondary cooling in a slab caster. It is also a common nozzle system for thin slabs, some beam blank and selective bloom and billet casters. The combined effect of air and water on the Leidenfrost point and the surface heat transfer associated with this transition, required analysis of multiple parameters rather than only the effect of volumetric flux.

The addition of air within a mixing chamber allows the water to be partially atomized prior to the effect of the nozzle orifice. Effects include reduction in droplet size as well as a change in the velocity of the spray. While tests have illustrated the volumetric flux was a primary parameter effecting heat flux over most conditions, the mean drop velocity was a significant variable for high-density sprays [1]. Tests examined the effects of three variables on heat flux; 1) Volumetric flux – Q, 2) Mean drop velocity - U_m , and 3) Sauter mean drop diameter – d_{32} . Volumetric flux provided a consistent influence in all areas. The effect of drop diameter was weak. However, the velocity was found to be important in high flux sprays, where Q was greater than $3.5 \times 10^{-3}\, m^3\, sec^{-1/m^{\wedge}2}$ [1].

High flux sprays tend to more closely define the characteristics created by industrial sprays. Within this group of sprays it had been found that correlations between mass flux and heat removal might be obtained. Unlike results found with mono-dispersed sprays, a spray pattern created by a nozzle creates significant interaction between the drops. This interaction was found to be dependent not only on the density of the droplets, but also on the relative drop size [3]. The indication here was that large droplets, over a range of 3 to 25 mm decreased in effectiveness as they became larger. The definition of effectiveness was considered as the ratio of heat flux over spray mass flux.

It has been found that sprays with constant velocity and drop diameters will yield a greater droplet density with increased mass flux. The increased density makes it more likely that the droplets interact with one another and the spray effectiveness would therefore decrease [2]. As spray density is increased, the surface condition eventually becomes flooded. The application of models based on dilute sprays has been found to over-predict the heat transfer values that result from increased mass flux. It has been suggested that this is a result of the interaction of the droplets increases as the sprays become denser and each of the droplets looses their individual effectivity [3]. Interaction within the sprays tends to reach a limit as pool boiling is reached when individual drop movement is restricted and mass flux becomes primary.

These considerations reach a new level when air and water are mixed and the dynamics of the sprays are further complicated. This paper will examine one aspect of the multi-faceted problem associated with spray effectiveness. By considering the result of less air within the nozzle spray, this single variable was isolated. The change in nozzle design created a more effective use of the air and the resultant droplet size was generally the same. Also, the nozzle size yielded the same flux density, by design. The opportunity therefore exists to consider only the effect of decreased air consumption and what that might mean to velocity and the interaction of the drops within the spray.

Experimental Setup and Data Reduction

Experiments were conducted on behalf of Spraying Systems Co. at the Department of Mechanical Engineering of Carnegie Mellon University. Complete information on the methodology was presented at the March 2002 Steelmaking Conference in Nashville, Tennessee in an “Experimental Study on the Cooling of High Temperature Metals Using Full Cone Industrial Sprays” [4]. The work at CMU was conducted over several years and sought to establish a database of typical spray nozzles that would be found in continuous caster secondary cooling locations. The range of spray density values tested provided a working range that was broader and therefore more applicable to current secondary cooling practices. The experimental setup is shown in Figure 3. It illustrates the location of the furnace, rail, pump and test chamber. Figure 4 provides a detail of the test plate, which incorporated a series of thermocouples, positioned approximately 2.5mm below the plate surface.

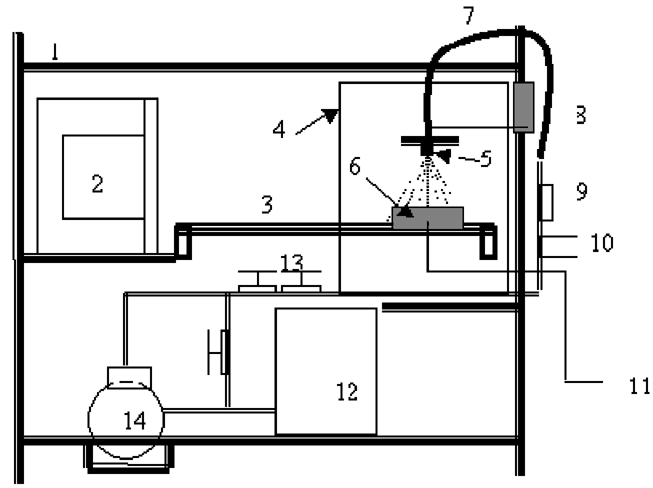

Figure 3: Experimental set-up

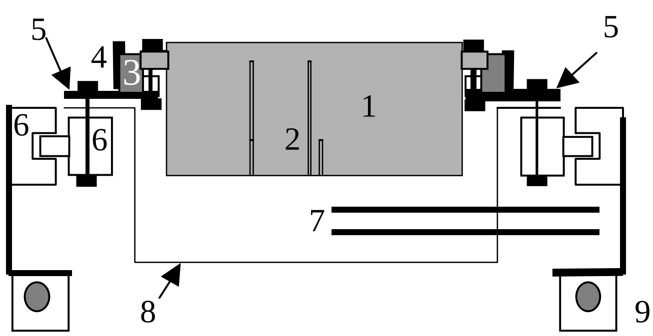

Figure 4: Test Plate and Rail

Data was collected at a spray distance of 152 mm for both mass flux values of the nozzles and heat transfer data during the test. Triangular weighted averaging was applied for data smoothing. These values were applied to the heat transfer calculations. Both direct and inverse conduction problems were solved in order to obtain the values at the plate surface.

Thermocouples were positioned within the test plate in order to measure the heat transfer and temperature. Direct conduction was recorded between probe 1 and 2. This was considered as a one-dimensional transient conduction problem with variable thermal conductivity for the temperature field. Inverse conduction was calculated from thermocouple 2 to the surface using Weber's method for linear transient conduction as follows [4]:

$$\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \qquad (1)$$

$$\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} + \gamma \frac{\partial^2 T}{\partial t^2} \qquad (2)$$

γ is a non-negative constant small enough to make equation (2) similar to (1).

T	Temperature (C^o)
k	Thermal conductivity (W/m*K)
Cp	Specific heat (J/kg*K)
x	Spatial variable
t	Time variable
ρ	Density
α	Thermal diffusivity (k/ρ* Cp)(m^2/sec)

With inverse heat conduction, the surface heat flux at time t depends on the interior temperature values at times both before and after t. Therefore, the numerical solution is obtained for all time steps at one spatial node before any temperature values are computed at the next spatial node [4].

$$\frac{(T_{i+1}^{n} - 2T_i^{n} + T_{i-1}^{n})}{(\Delta x)^2} = (1/\alpha) * \left[\frac{T_i^{(n+1)} - T_i^{(n-1)}}{2*\Delta t} + \frac{\gamma}{\Delta t^2} \left(T_i^{n+1} - 2T_i^{n} + T_i^{(n-1)} \right) \right] \qquad (3)$$

T_i^{n} Temperature at node (x_i , t^n)
Total time 300 seconds
Total spatial space (x3-x2)= 3.937 mm (0.155 inch)
Δx = 0.0667 mm Δt = 0.1 second
This explicit scheme, which is solved for T_{i+1}^{n+1}

Results

The purpose of this paper was to examine the similarity of the old and new CasterJet designs and the resultant heat transfer characteristics. Two nozzle sizes were tested of each design. The nozzle setups are identified with a number designation that indicate water flow in gallons per minute (gpm) at a condition of 100 psi, water and 45 psi, air. The two nozzle sizes were the 3 and 5, indicating 3 gpm, and 5 gpm, respectively. A simplifying assumption was made for this report by selecting data at a constant air pressure of 45 psi (3 Bar). This is a common operating condition for many casters, though in some cases the air and water pressure are both varied to provide a wider operating range of the secondary cooling water. The nominal spray angle of each of these CasterJets was 120 degrees. Variation in water pressure ranged from 0.7 Bar to 7 Bar.

Results of the tests considered for this comparison are limited to the transition point between high surface temperatures where film boiling is the dominant factor and where transition boiling begins. This is essentially the Leidenfrost Point and was measured as a transition point in the heat transfer curve. These values were plotted against the operating pressure of water with a constant air pressure and are shown in Figures 5 and 6. The significance of the point is worth some explanation. At high surface temperatures the vapor film acts as a barrier that prevents the spray droplets from direct contact with the steel surface. The result is a low heat transfer rate. This heat transfer rate is generally stable but does drop slightly as the temperature of the steel surface cools as it approaches the transition point where droplets begin to penetrate the steam barrier. Further cooling of the surface produces a change in the slope of the curve and a more rapid increase in the heat transfer rate begins. This point defines the start of the transition boiling regime. Secondary cooling in a continuous caster generally occurs above the transition boiling point. This relatively stable heat transfer rate provides a consistent level of cooling where variation of the water flow provides a direct means to provide a change in the cooling value.

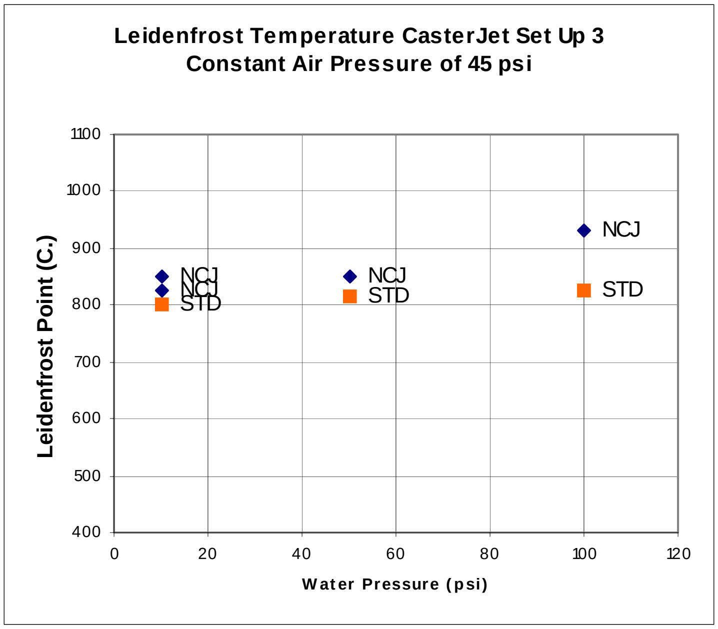

Figure 5: Setup 3 at Leidenfrost

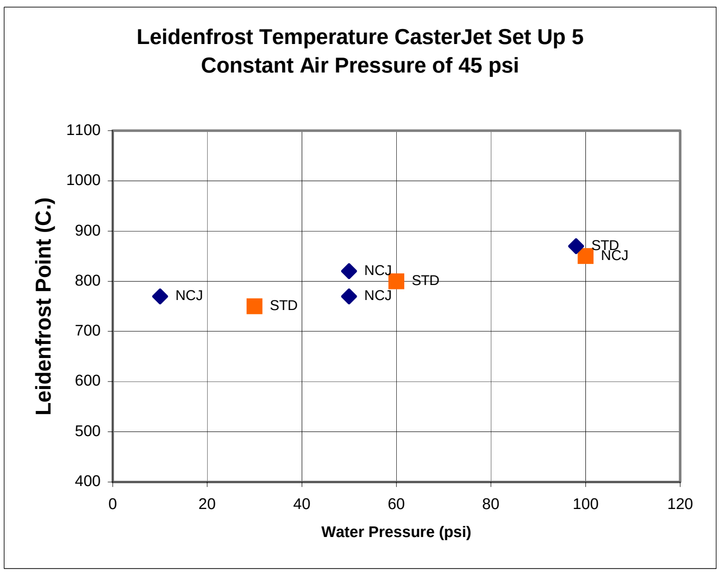

Figure 6: Setup 5 at Leidenfrost

The original CasterJet design was indicated as standard (STD) while the new model's data points were identified with NCJ. Standard CasterJet setup 3 was tested at a separate time and data series. The balance of the nozzles was tested together. In the case of the Leidenfrost Point, test results for the original design and the next generation CasterJet are similar. Water density, air volume, droplet size, and spray velocity are factors that affect the overall spray performance. However, the cumulative effect of these parameters does not appear to substantially alter the Leidenfrost Point except for the maximum tested water pressure of 7 Bar where a slight increase can be observed.

Surface heat flux is a useful measure of the spray nozzle's influence in the secondary cooling zones of continuous casters. As the surface of the steel is cooled the heat flux reaches a minimum value prior to the transition boiling point as previously described. This minimum value can be compared with other nozzles at various conditions in order to examine the characteristics of the sprays. Two separate heat transfer problems were solved in order to obtain the minimum values of heat flux at the surface. Direct conduction was applied between the location points of the thermocouples while inverse conduction solved the problem from the uppermost thermocouple to the surface. The results were then noted as the minimum heat flux for the spray nozzles.

CasterJets were of two sizes as noted previously, the 3 and 5 with 120 degree spray angles. The values shown were measured under the center of the spray at a distance of 152 mm. The minimum heat flux values for CasterJet setup 3 is illustrated on Figure 7. The Air pressure was a constant 3 Bar and the water pressure varied from 0.7 Bar to 7 Bar. Figure 8 shows the same data for setup 5. The original CasterJet design setup 5 was tested at an earlier time and scatter may be noted on the graphs. However, both the new and old setup 3 was tested together along with the new setup 5. There is better consistency in the data series of the three nozzles. Since the amount of published data available for this relationship is rather limited, the anomaly is included to allow for future study and analysis. The tendency is for higher water pressures to yield increases in the minimum heat flux. No attempt was made for this paper to isolate the effects of local mass flux of the spray or velocity effects of the air/water mixture. The cumulative effect of these parameters yielded increased minimum heat flux with increased water pressure while the air pressure was held constant. Furthermore, the minimum heat flux values for both the original CasterJet design and the NCJ CasterJet have similar heat flux values at similar conditions.

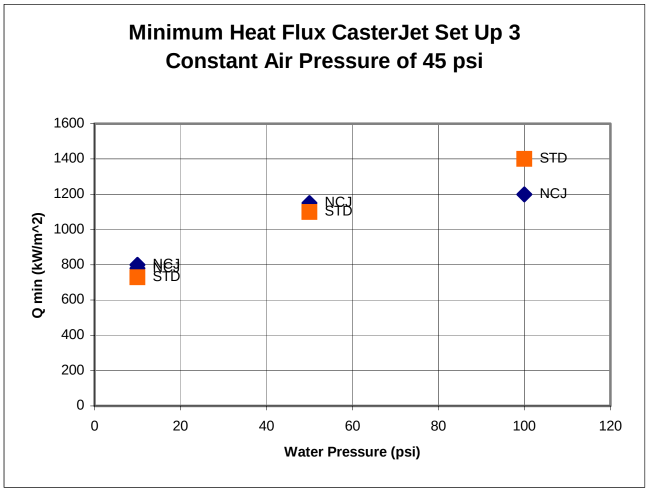

Figure 7: Setup 3 – minimum heat flux

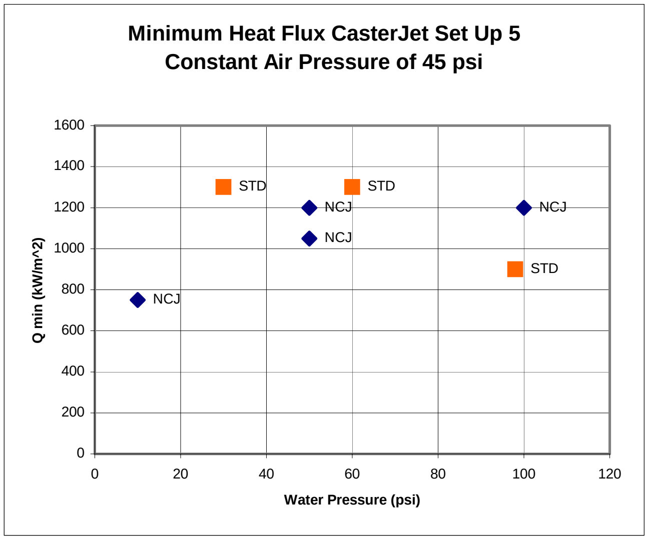

Figure 8: Setup 5 – minimum heat flux

The volume of air to the nozzle is based upon the inlet conditions to the mixing chamber. Data indicates that based on that variable there can be similar heat transfer results at the Leidenfrost point. Velocity of the air/water mixture to the exit orifice is not completely dependent upon that factor. Within a range the effectiveness of the nozzle geometry appears to provide sufficient changes to allow for similar drop size and velocity values that counter the reduction in air volume. This is not an obvious conclusion since in these nozzles the assumption is that increased air volumes will result in decreased drop size and increased velocity.

The spray, after exiting the nozzle orifice, was found to have similar volumetric distributions as measured by the specific flux density measures. Since the drop diameters are similar may be other factors that provide the heat flux results at similar levels regardless of these changes in air volume. Perhaps that is a result of the impact values caused by the spray hitting the surface. That would be consistent with previous assumptions that spray density and drop size combine to affect the heat transfer results. By considering a dimensional analysis of these factors it was found that if spray mass velocity replaced droplet velocity in the equations normally used to calculate Reynolds and Weber numbers, the correlation between parameters and spray heat transfer results were improved [3]. The results of these tests support that direction and suggest that a reduction of air volume by approximately 25% may not be significant as long as corresponding changes to the nozzle design provide similar effects upon these additional variables.

Conclusion

A reduction in the volume of air utilized in the CasterJet is of potential benefit by reducing operating costs of the continuous caster. The design improvements to the next generation CasterJet created an increased efficiency for the air and enhanced additional performance characteristics of the nozzle. Two descriptive measures of spray cooling for this application are the Leidenfrost Point and the minimum surface heat flux. Test results at constant air pressure and variable water pressure indicated that within the range of air volumes considered, these two values are similar from the original design to the new design, which uses reduced air volumes. Flux density of the spray is the primary determinant in providing surface heat flux values. The effects of spray velocity and the density of the spray appear to be important as contributing to the heat transfer conditions. Further analysis of these factors and the resulting impact of the spray onto the surface would be useful and may allow for correlations that are increasingly more predictable.

References

1. W.P. Klinzing, J.C. Rozzi, and I. Mudawar, "Film and transition boiling correlations for quenching of hot surfaces with water sprays," *Journal of Heat Treating*, 9, (1992), 91-103.

2. S. Deb, and S.C. Yao, "Analysis on film boiling heat transfer of impacting sprays," *International Journal of Heat and Mass Transfer*, 32, (1989), 2099-2112.

3. T.L. Cox, and S.C. Yao, "Heat transfer experiments and general correlation for impacting water sprays on high temperature surfaces," *Proceedings of 11th IHTC*, 3, (1998), 201-206.

4. Hamed M. Al-Ahamdi, S.C. Yao, Ken Kasperski, and Kristy Tanner, "Experimental study on the spray cooling of high temperature metal using full cone industrial sprays," *Proceedings of 85th Steelmaking Conference, Iron and Steel Society, Nashville, Tn.*, (2002), 365-376.