Essential Readings in Light Metals: Cast Shop for Aluminum Production.
Edited by John F. Grandfield and Dmitry G. Eskin.

EFFECT OF WATER QUALITY AND WATER TYPE ON THE HEAT TRANSFER IN DC CASTING

László I. Kiss[1], Thomas Meenken[1], André Charette[1], Yves Lefebvre[2], Robert Lévesque[3]

[1]Université du Québec à Chicoutimi
555 boul. de l'Université Chicoutimi, Québec, Canada, G7H 2B1

[2]GE Betz Inc.
2010 Winston Park drive, Suite 400, Oakville, Ontario, Canada, L6H 5R7

[3]Alcoa Aluminium Smelter in Baie-Comeau
100, route Maritime, Baie-Comeau, Québec, Canada, G4Z 2L6

Abstract

The mechanism of the boiling heat transfer in a falling film was studied experimentally in order to determine the cooling capacity of water in the DC casting. The experiments were based on the transient cooling technique. The quality (composition) of the water showed the strongest influence on transition between the different boiling regimes, on the character of the fluctuations of the surface temperature and heat flux.

Introduction

Although numerous papers have been published on the analysis of the heat transfer between the cooling water film and the solidifying ingot during DC casting (including comprehensive reviews, see for example 1,2,0,4), the research in this field continues (10). One important issue that attracted the attention of the researchers since long time is how the quality of the water affects its cooling capacity (5,6,7,8). However, as it was indicated in on of our earlier paper (11), there is no consensus in the literature about the quantitative indicators that describe the quenching capacity of the water. One possible approach is based on the determination of the correlation between the chemical analysis and the cooling capacity of the water (6). Another research direction is aimed toward the development of a methodology for the direct determination of the heat transfer characteristics of the water by quenching experiments (7,8).

The mechanism of the heat transfer between the falling water film and the solidified surface of the ingot in the secondary cooling zone is complex. The presence of three distinct phases, namely solid liquid and vapor in the contact zone creates a particular, dynamically changing spatial structure. Both the liquid and vapor can be found in continuous (liquid and vapor films) or disperse form (droplets and bubbles). The nucleation of vapor bubbles, the touching and repelling of liquid droplets along the rough solid surface introduce random fluctuations into the generally stable process.

For the description of this complex process, the terminology is transferred from the theory of multiphase heat transfer, more specifically from the pool and flow boiling. Although there are analogies with flow boiling, quenching, re-wetting in tubes and channels, the heat transfer and fluid flow in the free-falling liquid along a hot solid surface implies phenomena unknown in the other applications. Furthermore, the interpretation of the results obtained in laboratory scale - where the size of the sample, the character of the flow and the duration of the experiment can be very much different from that in real life – requires a thorough understanding of the underlying mechanisms.

In the present paper, we give a short summary of our work aimed at the improvement of the understanding of the physical mechanism of the cooling in order to correlate it with the type (composition) of the cooling water.

Experimental

The reproduction of the heat transfer phenomena of DC casting under laboratory conditions is not an evident and easy task. During the real casting process the surface temperature of the solidifying ingot in the secondary cooling zone varies from about 550-600 ℃ to lower than 100 ℃, while the peak value of the surface heat flux reaches the 5-7 MW/m^2 range. In an experimental rig with a relatively small cooled surface (for example 0.25mx0.5m), a heating power of about one MW needs to be introduced continuously into the specimen if steady state operation is required. Most of the published experimental studies are based on the transient cooling of a solid metal block that is preheated in a furnace before exposed to the water spray. There are researchers who test the quenching capacity of water by using small size specimens (so-called “missiles”) plunged into the water (subcooled pool boiling). The duration of these transient quenching tests depends on the size of the solid and it generally varies between a few seconds and a few minutes.

These experiments can never perfectly reproduce the real process for several reasons. If the cooling is too rapid, there is not sufficient time to establish the different flow boiling regimes with the same spatial structure as in the reality. Similarly, when the size of the solid is so small that it becomes commeasurable to the size of the vapor bubbles and to the vapor film thickness, the heat transfer characteristics do not correspond quantitatively to those measured along the surface of a real size ingot. Furthermore, the vertical temperature distribution of the cooled surface in the case of a stationary solid is different from that of the ingot moving downward during DC casting (Figure 1).

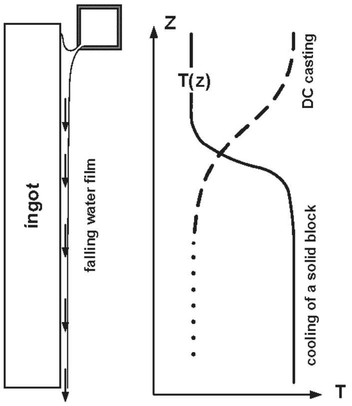

Figure 1. Character of the vertical temperature distribution along a water film cooled aluminum block.

While in the cast house, the water film meets colder and colder solid surfaces during its fall, in the experiments with stationary solid blocks the temperature gradient is the inverse.

Our experimental setup follows the transient principle (11). In order to approximate better the plant conditions, we selected a relatively big solid slab as specimen (height=500mm, width=300mm, thickness=50-80mm). This size permits to maintain the different boiling regimes along the solid surface for a few minutes. As it follows from the transient principle of operation, the limit between the different zones is slowly moving downward during the experiments. (The velocity of the vertical descent is about 2-5 mm/s).

The flow rate and inlet temperatures of the water are controlled and measured. The temperature sensors in the solid samples supply the primary data for the determination of the surface temperature-heat flux curves. The water quality is also tested regularly before and after measurements.

The ability of the test rig to accept samples with variable thickness allows for the adjustment of the cooling time by a factor of about two.

During the experiment, temperatures were measured in several points in the specimen. The method of temperature measurement along the water-cooled surface was described earlier (11). The surface heat flux distribution was calculated by solving the transient heat conduction problem inside the solid block by a finite volume numerical scheme. The temperature boundary conditions on the cooled front surface were measured directly in discrete points along the vertical centerline. Between the measured points, a transient interpolation method was used to supply boundary conditions for all the surface nodes. The applied numerical procedure permits to evaluate both the normal and tangential components of the surface heat flux. The character of the distribution of the normal components of the heat flux is shown in Figure 2. In the given instant the rewetting zone is about halfway down along the plate as the position of the highest peak shows. The second highest heat flux is at the impingement point, while a third, relatively small peak can be seen below the rewetting zone. The latter corresponds to an instantaneous wet-contact between the separated liquid film and the solid (see discussion later).

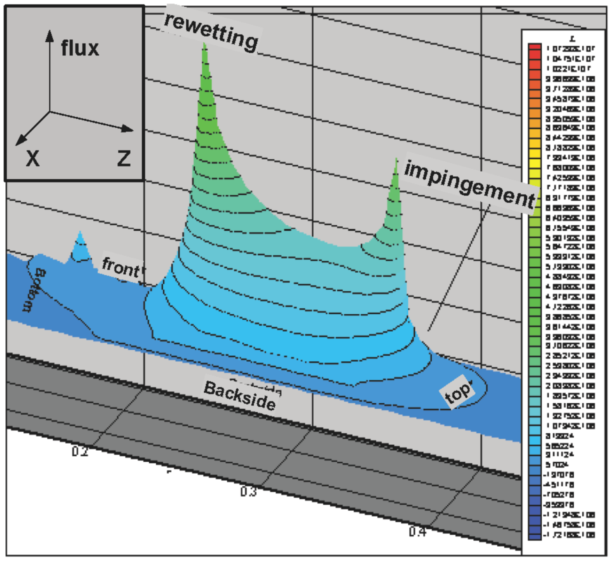

Figure 2. Heat flux distribution along the surface of the test specimen as identified from the surface temperature measurements.

The “null-calorimeter method” of surface temperature measurement as it was realized in our experiments, permitted to follow the fast temperature and heat flux fluctuations that exist in the impingement zone and elsewhere when the wavy motion of the water film results in instantaneous wet-contact spots.

Influence of the water quality on the cooling process

In single phase heat transfer (natural and forced convection) it is relatively easy to determine which material properties influence the heat transfer coefficient and how they do that. The thermal conductivity is the principal influencing property followed by the density, viscosity, specific heat and thermal expansion coefficient.

In DC casting – similarly to other boiling applications – the contact between the primary cooling agent the liquid and the solid is perturbed by the presence of a bad thermal conductor, the vapor. The morphology of the two-phase layer is complex in both space and time. The liquid water can be completely separated from the solid by a stable vapor film, or the liquid-solid contact can fluctuate, creating instantaneous and alternating wet-spots along the surface.

The intensity of the heat transfer can vary at least two orders of magnitude between the "wet" and "dry" contacts. In the impingement zone, a surface point can be wetted and dried out several times during one second. These relatively fast fluctuations affect a few millimeter thick layer under the surface, below that layer only the average or mean value of the surface heat removal rate is sensible. The time-averaged value of the heat transfer coefficient is strongly affected by the frequency and shape of the fluctuations between the two states. For example, if within one period of the fluctuation, the duration of the wet-contact becomes 10% longer than that of the dry one, the effect on the average heat flux will be much stronger than a 100% increase in the thermal conductivity of the liquid water.

The rate of the collapse of a vapor bubble, the velocity of the movement of the triple-contact line (where the solid, liquid and vapor phases meet), the wetting angle and consequently the shape of the liquid-gas interface all depend on the surface or more precisely on the interface tension values in the three-phase system. All of our observations support the conclusion that the overall heat transfer rate is strongly influenced by the size and duration of the wet-dry contact zones along the ingot surface. From this perspective, the influence of water quality plays a role basically through the modification of the spatial structure and temporal fluctuations of the two-phase region in the falling film.

The above outlined mechanism also explains why the size and geometry of the solid to be cooled can influence the average value of heat extraction rate. During the quenching of too small specimens, whose curvature is commeasurable to that of the generated bubble interfaces, the attachment of the liquid and vapor films or bubbles is different from that along large flat surfaces. In addition, the quenching of too small solids does not let sufficient time to develop thermally and even mechanically stable vapor-liquid structures. These physical tendencies can be well recognized in the findings about the effect of surface roughness on the ingot cooling (4,11).

The above-mentioned tendencies are illustrated in Figure 3, where the cooling capacity of three different water types is characterized by the surface temperature variations and by the computed heat flux values. The overall character of the temperature and corresponding heat flux curves is similar, the part of the curves that describes the stable vapor film is nearly the same. The greatest differences are in the fluctuating region, where the wet-dry contact conditions alternate.

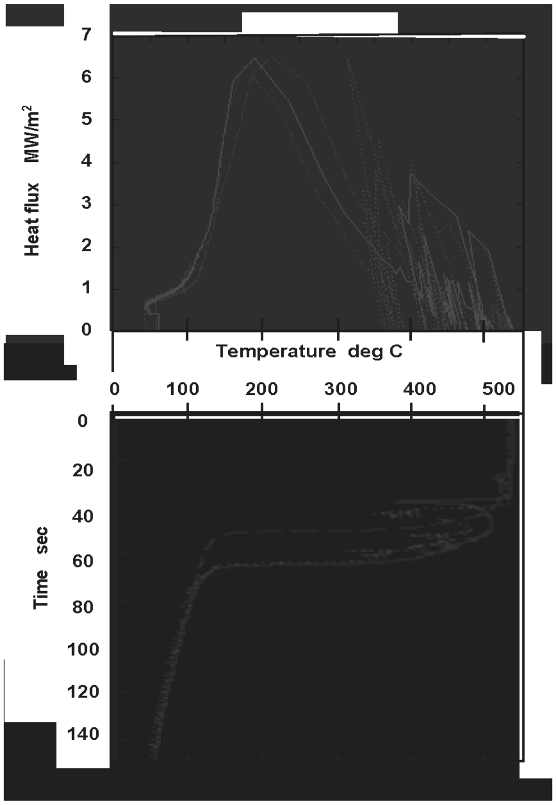

Figure 3. Surface temperature variations in time and the corresponding heat flux values measured 85 mm below the impingement point. The curves correspond to three different water compositions.

Figure 4. Repelled water droplets in the impingement zone, at the very first instants of the cooling.

The temperature histories were measured locally, in discrete points, so the curves in Figure 3 inform us only about the temporal fluctuations in the given point. However, the wet and dry contact zones alternate dynamically also along the cooled surface. To reveal these structures, we recorded the structure of the falling film by a video camera simultaneously with the temperature measurements.

In Figure 4, the shape and distribution of the water droplets, repelled from the hot surface in the impingement zone, are shown. The size of the droplets is in the order of few millimeters. The phenomenon is illustrated schematically in Figure 5. A few milliseconds later, the character of the water-solid contact changes, see Figure 6. There are droplets that wet the surface, their size is bigger than in the previous image, but they are still separated by "dry" zones, where the solid is in contact only with vapor.

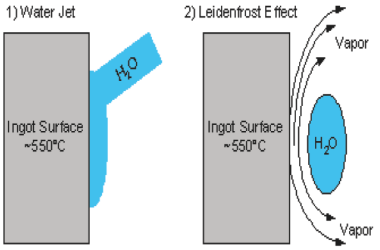

Figure 5. Repelling of the liquid from the hot surface (Leidenfrost phenomenon for a vertical wall).

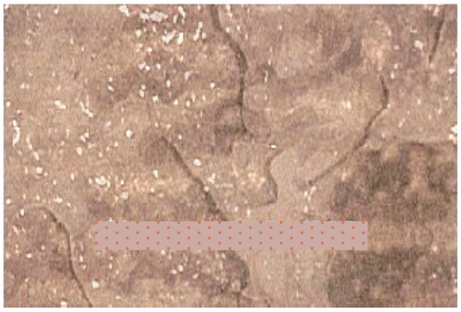

Figure 6. Structure of the water film in the impingement zone, few milliseconds after the previous photo.

Another example about the effect of water composition is shown in Figure 7. In the upper graph - that corresponds to higher oil content than the lower one – the fluctuations that precede the formation of the stable vapor film are much weaker. In other aspects, the curves are very much similar.

Structure of the falling water film

In the lower graph of Figure 7 an interesting phenomenon can be observed: the onset of the strongest fluctuations is identical in all the four measurement points. This feature of the cooling curves was present in the majority of the experiments where relatively strong fluctuations were recorded. As about 300 millimeter difference is between the first and fourth thermocouple, there must exist a mechanism that triggers those fluctuations along the ingot surface at a relatively great distance. It is clear from the recordings that these fluctuations cannot be linked to the re-wetting. The re-wetting zone passes at front of the measurement points with a slow, nearly constant velocity as the equal distances between the temperature drops indicate.

In order to correlate the temperature recordings with the video images, the experimental technique was modified. Four semiconductor lasers were installed in such a way that the beam from each of them was directed to one of the surface temperature measurement points located along the centerline of the solid specimen (Figure 8). The lasers were switched on by the data acquisition system when the temperature reached the re-wetting value.

The analysis of the video images obtained during the quenching tests revealed the mechanism that synchronizes the fluctuations along the height of the ingots.

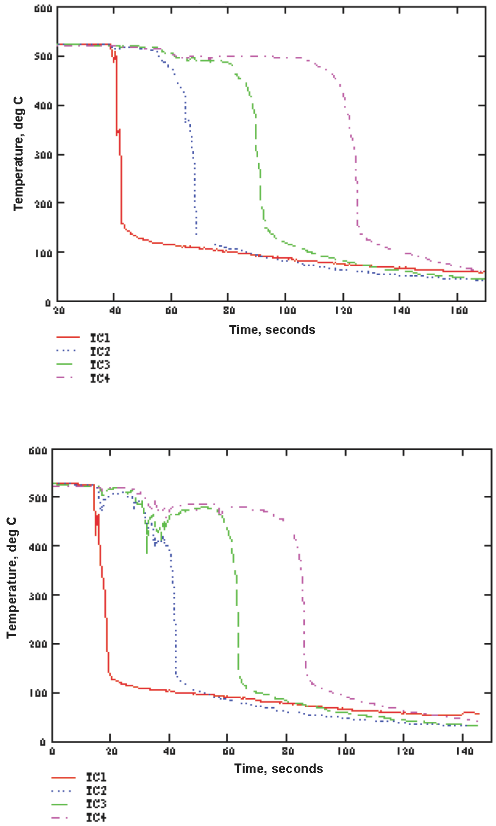

Figure 7. Cooling curves measured in four points along the vertical centerline of the solid specimen. The two curves were obtained by using waters with different oil content: the upper curve corresponds to a higher oil content.

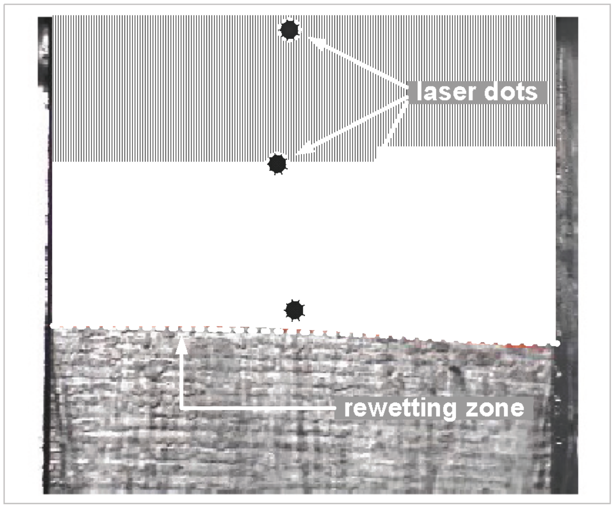

Figure 8. Laser dots were projected to the surface at the position of the surface thermocouples when the temperature dropped below a preset value.

The structure of the falling water film is shown schematically in Figure 9 and Figure 10.

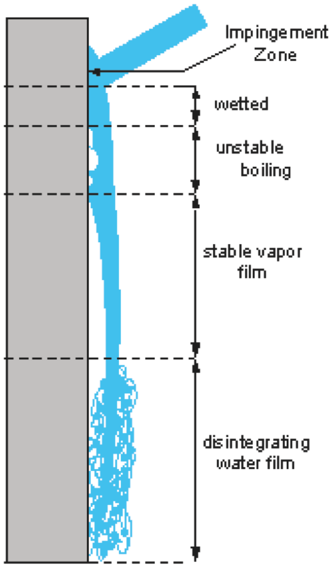

Figure 9. Structure of the falling water film (vertical section).

Vertically the whole film can be divided into 5 zones: impingement and wetted zones, unstable (oscillating) boiling, stable vapor film and the zone where the falling liquid film disintegrates. The vertical dimensions of these zones are not proportionally shown in the schema; the limits between the zones are also strongly schematic. It was especially difficult to visualize and to observe the phenomena in the unstable boiling zone, which is vary narrow.

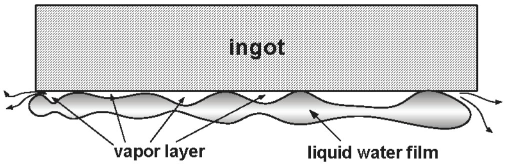

Figure 10. Structure of the falling film: irregular, wavy shape of the liquid film (horizontal section).

The surface of the falling liquid water film that is separated from the solid by the vapor cushion is irregular, wavy as it is shown in Figure 10. In addition, that surface is not stable; it vibrates so that its distance from the solid varies. As the schema in Figure 10 indicates, the vapor film cannot separate the liquid from the solid everywhere uniformly; there is a chance for the water to get temporarily into direct contact with the solid.

The vibrations of the liquid film are somewhat similar to that of an elastic membrane, a major part of it moves in the same phase. This means that when the liquid film touches the solid surface, it happens generally not only in a single point but along a vertical line or in multiple zones. Figure 11 shows an instant when several relatively large wet-contact spots were formed simultaneously. These wet-spots have a short life, as they are rapidly repelled from the solid that is still hotter than the corresponding Leidenfrost temperature.

The synchronism of the measured fluctuations can be explained when these oscillations of the liquid film have a wavelength that covers a large portion of the cooled surface, then the wet-contact zone can be created simultaneously at the different measurement points.

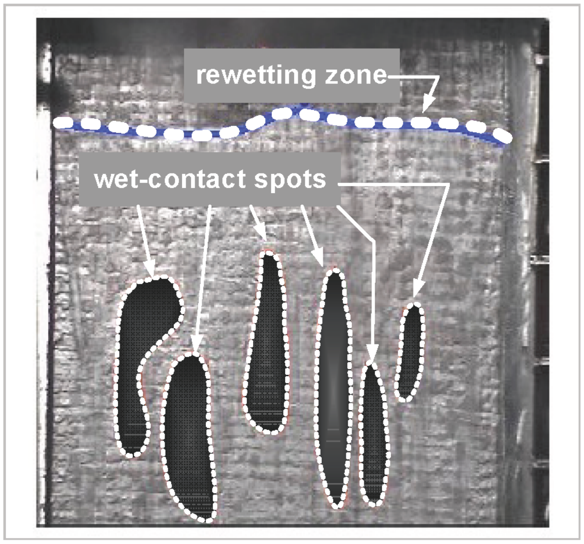

Figure 11. Instantaneous contact spots between the water film and the surface of the ingot.

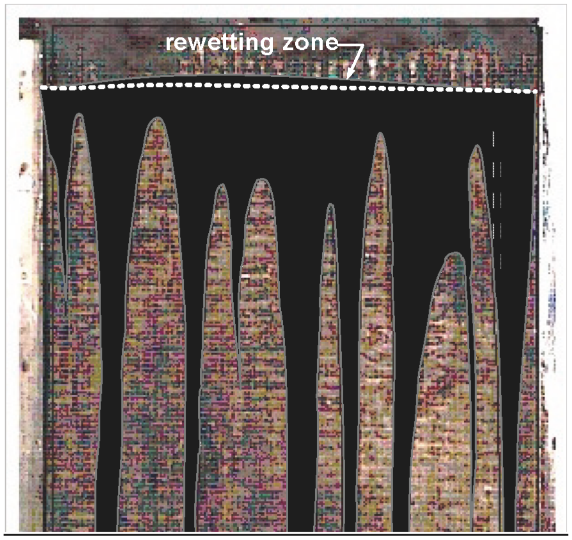

Figure 12. Breakup of the falling film, formation of rivulets.

The shape and fluctuations of the liquid film vary strongly from one set of conditions to the other. Right below the re-wetting zone the film is nearly smooth, continuous. The waviness increases downward for two main reasons: the film accelerates due to the gravity, reducing the cross section and the surface forces tend to form circular jets from the planar one. Under certain conditions, the falling liquid film disintegrates into rivulets, as it is shown in Figure 12. The formation of these rivulets was already described mathematically liquid films wetting the solid (9), the case when the liquid is separated by a vapor cushion needs further analysis.

It must be also emphasized that the above outlined mechanisms that determine the shape, distribution and fluctuation of the dry and wet contact zones contain many uncontrollable parameters that introduce a random variation into the cooling process. The random character is more pronounced when we consider smaller regions along the ingot surface and shorter time scales. Although we judge the reproducibility of the cooling experiments to be good (11), the difference between two experiments repeated under the same conditions is always bigger than the precision of the measurements. The small non-homogeneities on the solid surface, the surface roughness, the smallest deposition of the dissolved salts on the surface, the turbulent fluctuations in the arriving water jets etc. all can affect the pattern and fluctuation of the dry and wet contact zones.

Conclusions

The experimental work revealed many complex features of the spatial structure and of the fluctuating character of the falling water film in DC casting.

There are strong variations of the local heat transfer rate on the few millimeter scale along the ingot surface, especially in the impingement zone. Dry and wet contact spots alternate in a more or less random pattern. In addition, the local heat flux fluctuates in time, and its mean value is strongly influenced by the ratio between the duration of the dry and wet contact periods.

In the zone of stable film boiling, the water film starts to vibrate and disintegrate during its downward travel. The wavy, oscillating motion and the formation of rivulets can bring the liquid into a temporary direct contact with the surface of the ingot, resulting in an increase of the heat transfer rate locally well before the complete re-wetting.

The water composition affects the most sensitively the cooling rate through the variation of the spatial and temporal distribution of the wet and dry contact zones between the water and ingot. Besides the experimental findings reported here, this tendency is confirmed by the success of certain quench-control methods. The pulsating (water on-off) method controls the duration of wet and dry contacts, while the application of dissolved gases controls their spatial distribution, generating more bubbles (dry-spots) along the cooled surface.

Acknowledgment

The work presented in this paper was made possible by the support of the companies GE Betz, Alcoa and of the Quebec Aluminium Research and Development Center (CQRDA).

References

1. J. Grandfield, A. Hoadley, A. Instone, “Water Cooling in Direct Chill Casting: Part 1, Boiling Theory and Control, Light Metals, TMS, 1997, 691-699.
2. L. Maenner, B. Magnin, Y. Caratini, "A comprehensive approach to water cooling in DC casting", Light Metals, TMS, 1997, 701-707.
3. M. Bamberger, B. Prinz, ”Determination of heat transfer coefficients during water cooling of metals”, Materials Science and Technology, April 1986, V.2, 410-415.
4. D. Li, M.A. Wells, G. Lockhart, “Effect of surface morphology on boiling water heat transfer during secondary cooling of the DC casting process”, Light Metals, TMS, 2001, 685-692.
5. H. Yu, "The effect of cooling water quality on aluminum ingot casting", Light Metals, TMS, 1985, 1331-1347.
6. H. Yu, D.D. Leon, A. Giron, "A sensor for monitoring the heat transfer characteristics of ingot cooling water containing dissolved gases", Light Metals, TMS, 1994, 779-786.
7. J. Langlais, T. Bourgeois, Y. Caron, G. Béland, D. Bernard, "Measuring the heat extraction capacity of DC casting cooling water", Light Metals, TMS, 1995, 979-986.
8. A. Larouche, J. Langlais, T. Bourgeois, A. Gendron, "An integrated approach to measuring dc casting water quenching ability", Light Metals, CIM, 1999, 235-245.
9. Hamed Saber, Mohamed El-Genk, “Velocity field in stable rivulets, following breakup of liquid films flowing down a vertical, uniformly heated wall”, Proc. 12the Heat Transfer Conference,, Elsevier, 2002, Vol.3, 839-844.
10. E. A. Sorheim, D. Mortensen, S. Benum, C. Stette, “Inverse analysis of space and time variations in the boundary heat flux during water film cooling”, Light Metals, TMS, 2002, 679-686.
11. L. I. Kiss, T. Meenken, A. Charette, Y. Lefebvre, R. Lévesque, “Experimental study of the heat transfer along the surface of a water-film cooled ingot”, Light Metals, TMS, 2002, 981-987.

Essential Readings in Light Metals: Cast Shop for Aluminum Production.
Edited by John F. Grandfield and Dmitry G. Eskin.

Recommended Reading

Bryson, N.B. Increasing the productivity of aluminum DC casting (1972, pp. 429–435).

Fortina, G., and F. Gatto. Thermal distribution during ingot solidi.cation of DC casting (1978, pp. 365–380).

Fossheim, H., and E.E. Madsen, Application of a mathematical model in lever-pour DC casting of sheet ingots (1979, pp. 695–720).

Giron, A., and J.E. Jacoby. Design of molds to minimize internal shrinkage cavities in sows (1993, pp. 855–861).

Grandfield, J.F., et al. Water cooling in direct chill casting: Part 2, effect on billet heat flow and solidification (1997, pp. 1081–1090).

Grealy, G.P., et al. Advances for DC ingot casting: Part 1 – introduction and melt distribution (2001, pp. 805–811).

Grün, G.U., I. Eick, and D. Vogelsang. 3D-modelling of flow & heat transfer for DC-casting of rolling ingots (1994, pp. 863–869).

Jensen, E.K. Mathematical model calculations in level four DC-casting of aluminium extrusion ingots (1980, pp. 631–642).

Jensen, E.K. Mould temperatures during DC-casting of 8 inch diameter extrusion ingots in alloy 6063 (1984, pp. 1159–1175).

Kiss, L.I., et al. Experimental study of the heat transfer along the surface of a water-film cooled ingot (2002, pp. 981–985).

Kraushaar, H., et al. Correlation of surface temperature and heat transfer by D.C. casting of aluminium ingots (1995, pp. 1055–1059).

Langlais, J., et al. Measuring the heat extraction capacity of DC casting cooling water (1995, pp. 979–986).

Lawrence, R.R. Cross-section shape control of D.C. sheet ingot using a flexible mould (1976, pp. 457–463).

Lucas, G. Auto control of D.C. casting operations (1974, pp. 635–638).

Maenner, L., B. Magnin, and Y. Caratini. A comprehensive approach to water cooling in DC casting (1997, pp. 701–707).

Meier, H.A., G.B. Leconte, and A.M. Odok. Alusuisse experience with electromagnetic moulds (1977, pp. 223–233).

Moriceau, J., and P. Heuillard. Automation of slab casting (1984, pp. 1103–1110).

Moritz, C.J., W. Schneider, and H.P. Krug. Melt flow in spout-stopper systems and its impact on metal quality in aluminium cast houses (1996, pp. 639–646).

Peterson, R., R. White, and R. Downie. Development and verification of DELPEC sow mold (1992, pp. 999–1005).

Wagstaff, R.B., and K.D. Bowles. Practical low head casting (LHC) mould for aluminium ingot casting (1995, pp. 1071–1075).

Yu, H. The effect of cooling water quality on aluminium ingot casting (1985, pp. 1331–1348).

Zuidema, J., Jr., et al. Secondary cooling in DC casting: Modeling and experimental results (2001, pp. 873-878).