Pool Boiling Cooling for Melt Spinning Quench Wheels

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The production of rapidly quenched metal ribbons by melt spinning on a cylinder produces very high average heat fluxes through the cylinder. The problem of maintaining a low average casting surface temperature can be solved by boiling on the plain interior of the cylinder. An experimental, boiling cooled, amorphous iron alloy ribbon casting wheel was constructed to verify the concept and expand the available data on boiling heat transfer. Experiments were performed with water, near atmospheric pressure, in pools less than 0.03 m deep and at accelerations between 100 and 200 times earth gravity. Heat fluxes between 0.6 and 3.5 million W/m² were achieved. Heat transfer coefficients up to 0.1 million W/m²·K were measured. A loss of cooling occurred in a number of instances, at heat fluxes well below the predicted critical heat flux, and at heat flux conditions which were duplicated or exceeded in the remaining experiments. These conditions, possibly precipitated by local variations in the boiling heat transfer coefficient, are not considered to represent new boiling phenomena associated with high acceleration.

I. INTRODUCTION

Melt spinning rapid solidification involves applying a molten metal alloy to the outside surface of a rotating wheel. A thin ribbon of alloy is drawn from the melt and quenched by the wheel surface. The problem of maintaining a low average casting surface temperature for continuous ribbon casting can be solved in a variety of ways: single phase forced convection, forced convection boiling, film vaporization, spray cooling, and pool boiling. In laboratory devices, where wheel size and cost are relatively unimportant, any of the cooling methods might be implemented to suit particular needs. The key advantage offered by pool boiling for production devices is simple geometry: a capped, plain hollow cylinder with a liquid feed and vapor exit port. Excellent uniform heat transfer in the boiling, centrifugally accelerated, annular liquid layer does not require finned heat exchange surfaces, flow constrictions to increase convection, or thick cylinder walls for heat spreading; as a result, cylinder wall thickness is dictated by mechanical design, wheel compactness is maximized, and axial scalability is straightforward. The complexity of auxiliary equipment will depend on the choice of boiling fluid and operating pressure, but in the simple case of atmospheric boiling water, inexpensive, low pressure, rotating seals may be used to vent steam directly without heat exchangers.

The casting surface of the wheel sees extreme variations in applied heat flux, but in many cases this variation will damp out to present the interior with a circumferentially average flux. Although boiling may be suitable in cases with circumferential variations in heat flux, the analysis is more complicated and must include the effects of ribbon to wheel heat transfer.

II. POOL BOILING

The convection heat transfer of forced flow systems is replaced by bubble induced convection in pool boiling cooled designs. The increasing bubble generation with heat flux results in rapidly increasing boiling heat transfer coefficients. While a number of correlations are available for predicting heat transfer coefficients in pool boiling, problems exist in their use for melt spinning applications. The key problems are that acceleration is either ignored or predicted to have a significant effect in various correlations, and melt spinning produces heat fluxes which are generally much higher than those of the data used to construct the correlations. An example of a pool boiling correlation based on bubble microconvection phenomenology and including an acceleration dependence, is the widely cited correlation of Rohsenow\(^1\) (Eq. [1]). The accuracy of the correlation in accounting for flux and fluid property effects in boiling is adequate and well documented at one gravity acceleration; however, the predicted heat transfer coefficient dependence on acceleration to the 0.5 power is in disagreement with the experimental results of Costello and Tuthill,\(^2\) Merte and Clark,\(^3\) Eschweiler et al,\(^4\) Adelberg and Schwartz,\(^5\) and Marto and Gray.\(^6\) These investigators, working with atmospheric pressure water, found acceleration dependence only in heat flux regimes with a natural convection component of heat transfer. The maximum heat fluxes achieved in these various experiments were not significantly higher than have been achieved in earth acceleration boiling experiments and, as a result, provide little aid in selecting a boiling correlation for extrapolation to very high fluxes. Lacking a firm basis for choice, Rohsenow's correlation, with the acceleration dependence ignored (set to earth gravity in Eq. [1]), has been used in the following sections to account for the boiling heat transfer effects of flux and boiling fluid property changes. The fluid property changes occur as a result of pressure variations at the boiling surface due to high acceleration on shallow pools and external pressure regulation.

\[
\frac{C_p(T_w - T_b)}{h_f} = C_r \left[ \frac{q''}{\alpha h_f \left( \frac{\sigma}{a(p_1 - p_2)} \right)^{0.5} \nu^{0.33}} \right] Pr^{0.5} \quad [1]
\]

A sufficiently high vapor generation rate at the boiling surface will lead to vapor blanketing, with severely reduced heat transfer. The critical heat flux at which this occurs is governed by hydrodynamic instabilities represented in the equation of Kutateladze\(^7\) (Eq. [2]). Acceleration, fortuitously present in melt spinning, has a substantial direct and
beneficial effect on critical heat flux, an effect verified by Costello and Adams,9 Morozkin et al.,10 Usenko and Fainzil’Berg.12 An additional effect of the acceleration is to increase the pressure at the boiling surface; since the vapor density of, for instance, water near or below atmospheric pressure is a very strong function of pressure, the vapor density, hence critical heat flux, will substantially increase with pool depth and acceleration.

\[ q'' = 0.16h_{bg} \rho_c \left( \frac{\alpha_{bg} (\rho_f - \rho_g)}{\rho_c^2} \right)^{0.25} \]  

[2]

The design of a boiling cooled wheel must contend with the multiplicity of parameter choices available: pool depth, wheel diameter, operating pressure, coolant fluid, cylinder thickness and conductivity, casting surface speed and temperature, and ribbon thickness and temperature. Complicating the problem are constraints imposed by mechanical design and critical heat flux. Finally, the total applied heat and casting surface temperature cannot, in principle, be calculated independently. An example of a design procedure has been prepared with several simplifications: (a) atmospheric-pressure boiling water with zero pool depth, (b) the total applied heat is independent of casting surface temperature, (c) casting surface speed and average temperature are the critical wheel parameters in determining a melt spinning setup, (d) casting cylinder thickness is small compared to wheel diameter, and (e) wheel diameter and cylinder heat transfer conductance are adjustable parameters. Under these assumptions, Figures 1 and 2 have been constructed with Eqs. [1] \((C_{sf} = 0.013)\) and [2] determining the boiling effects.

To use Figures 1 and 2, the total energy per unit ribbon area, released by the ribbon to the wheel \((Q)\) must be calculated; this quantity depends on initial melt temperature, metal specific heats, heat of fusion if a phase transition is involved, ribbon thickness, and the (estimated) final ribbon temperature. In Figure 1, critical heat flux limits for some possible values of \(Q\) determine the minimum wheel size; any larger size is acceptable. The angular velocity determined from Figure 1 is easily converted to heat flux in Figure 2 where the choice of the casting surface temperature \((T_c)\) will dictate the needed cylinder conductance. Inability to achieve the desired conductance in the material of choice while satisfying mechanical requirements will require a larger wheel; the graphs may then be used in reverse order. A specific example, represented on Figures 1 and 2 with a dashed line, is an iron alloy ribbon of 25 μm thickness to be cast at a surface speed of 20 m per second while maintaining an average casting surface temperature under 570 K. The energy released per unit area of ribbon is approximately 100,000 J/m². According to Figure 1, a 0.10 m diameter wheel represents the minimum size, so a choice of 0.4 m is entirely acceptable and provides an acceleration well over 50 a/g, so the effect of earth gravity on the acceleration is less than ±2 pct. Operating this wheel at the required 1000 rpm results in a heat flux of 1.6 million W/m². Using a rim with a 10,000 W/m² • K conductance (equivalent to a typical steel alloy rim of 0.005 m thickness), a casting surface temperature below 570 K is achieved.

The graphs illustrate the dominant influence of cylinder conductance on wall temperature; for conditions chosen on