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Flow control in a subcooled tube: an experimental investigation of the effects of crust formation

J. S. PITSILLOS, Y. L. YEOW and N. B. GRAY†

G. K. Williams Cooperative Research Centre for Extractive Metallurgy, Department of Chemical Engineering, The University of Melbourne, Parkville, 3052, Australia

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Abstract—The flow control of molten liquids in tubes by manipulating the flow cross-sectional area using solidification has been investigated. Eicosane, because of its well characterised thermophysical properties, fixed melting point and known temperature dependent properties, was used as the test fluid. The eicosane data can be used to model the flow control of high temperature slag in the metallurgical industry and to verify the results of mathematical models of slag flow in tubes. Experimental results are presented in the form of pressure drop vs flow rate and dimensionless freezing parameter (Tw^*) vs flow rate. These are compared with a theoretical laminar flow model with solidification. The experimental results cover: $100 < Re < 1000$, $0.3 < Tw^* < 5.4$ and for cooled length to diameter ratios (L/D) of 41.9, 27.6, 26.3 and 19.8. For $Tw^* < 4$ the agreement between experiment and theory is within 20%. For $Tw^* > 4$ it was clearly observed that the experimental pressure drop is significantly lower than the theoretical predictions and can be attributed to either the breakdown of the laminar flow assumption and/or the formation of an air gap between the tube and the solidified crust. © 1997 Elsevier Science Ltd.

INTRODUCTION

Solidification of molten liquids in ducts and pipes encountered in many liquid transport processes may have detrimental side effects. Some examples of molten liquid transport with solidification include transport of water in pipes in cold regions, freezing of liquid metals in heat exchangers, metal and slag solidification in tapholes during furnace tapping and freezing of polymers in injection moulding. Solidification with fluid flow has not been used in the past for flow rate control. When a molten liquid is highly aggressive and conventional flow control methods are inapplicable then it maybe feasible to use partial solidification of the fluid flow to control the flow rate. For the case of furnace tapping, due to the above-mentioned reasons conventional flow control methods are inapplicable and current technology is labour intensive, hazardous and does not allow utilisation of the furnace to its maximum potential. Therefore, some fundamental investigations for flow rate control have been carried out with the aim of controlling the flow rate of molten liquid furnace products using solidification.

SCOPE

The scope of the present work is to carry out laboratory scale experiments to investigate the probability of exploiting solidification (crust formation) as a means of flow control and to experimentally verify that the theoretical minimum pressure drop obtained by the mathematical model is the blockage point. The experimental data when compared with the results derived from the model are used to provide some guidelines for the operation and design of tapholes. The variation of pressure with volumetric flow rate under different freezing conditions and tube geometries was measured experimentally. Results are presented in terms of the pressure drop (P^*) versus flow rate (Re) and the degree of cooling (Tw^*) vs flow rate (Re) curves for various flow geometries (L/D).

PREVIOUS WORK

There are a number of comprehensive review articles in the area of solidification in a duct with internal forced flow [1–3]. In the classical paper of Zerkle and Sunderland [4], the problem of steady-state tubular laminar flow with solidification and constant tube wall temperature, was investigated. The problem is shown schematically in Fig. 1. The tube wall is maintained at a uniform temperature (T_w) below the freezing temperature of the liquid (T_f). The liquid enters the tube at a uniform temperature (T_o) higher than the freezing temperature (T_f). The tube of radius (R), has crust buildup on the wall. The crust thickness increases with axial distance from the entrance of the tube. R_c denotes the radial position of the crust liquid interface as a function of axial distance (z). Zerkle and Sunder-

† Author to whom correspondence should be addressed.

NOMENCLATURE

C_p	liquid heat capacity
D	tube diameter
k_L	liquid thermal conductivity
k_s	solid thermal conductivity
L	tube length
L/D	length-to-diameter ratio
Pe	Peclet number $PrRe$
Pr	Prandtl number $(C_p\mu)/k_L$
P	pressure drop in tube
P^*	dimensionless pressure drop $P/[\mu^2/(8R^2\rho)]$
r	radial coordinate
R	tube radius
R_c	radial position of solid–liquid interface
Re	Reynolds number $(2VR\rho)/\mu$
T_e	liquid exit temperature
T_f	freezing/melting temperature
T_o	liquid inlet temperature
T_w	tube wall temperature
Tw^*	dimensionless freezing parameter $k_s(T_f-T_w)/k_L(T_o-T_f)$
V	average velocity
V_z	axial velocity
z	axial coordinate.

Greek symbols

μ	liquid viscosity
ρ	density.

Subscripts

e	exit
f	freezing point
L	liquid
o	inlet
p	pressure
s	solid
w	wall.

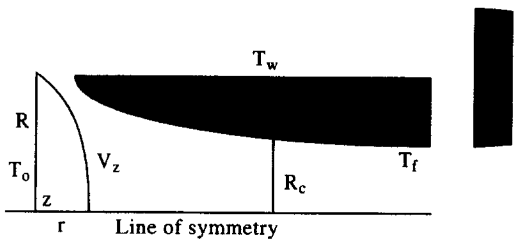

Fig. 1. Schematic diagram of solidification with fluid flow in a tube.

land obtained a solution for this problem in the form of an infinite series by making the simplifying assumption that the velocity is parabolic in the liquid core and that axial conduction is negligible. Pitsillos *et al.* [5] using a finite element model (FEM) solved the same problem without these restrictive assumptions and showed that for $Pe > 100$ when axial conduction becomes insignificant, the finite elements results and that of Zerkle and Sunderland [4] are in good agreement.

Pitsillos and Gray [5–10] introduced the concept of a new furnace tapping technique involving the simulation of a control valve at the exit of a furnace using solidification to control the flow rate. Experiments were carried out on non-ferrous slags [6] and the results were in reasonable agreement with theory given that the experiments were carried out under pseudo-steady-state conditions, the slags did not have a single melting point and the temperature dependent properties were not accurately known. The experiments were for pseudo-steady-state because the furnace level decreased continuously during the experiments and thus the assumption of constant pressure was not totally correct. The experimental conditions were $50 < Re < 1000$, $53 < Pr < 170$, $4.2 < Tw^* < 6.1$, $L/D = 7.5$ and $5E5 < P^* < 1E7$. The results indicated that the experiments were consistent with the theory and the theoretical trends were followed. However, these experiments were not adequate to verify the model.

Subsequent work by Harris *et al.* [11] and Stewart *et al.* [12] has focused on the case of flow control of molten metals using solidification and carried out experiments on molten lead. Harris *et al.* [11] presented a mathematical model for calculating the valve head loss vs flow rate relationship under turbulent flow in a convectively cooled circular pipe. Stewart *et al.* [12] carried out experiments on flow control of molten lead in a convectively cooled tube. Their results indicated the ability of a convectively cooled tube to alter the flow rate of the lead and the results were in reasonable agreement with the theory. Pitsillos *et al.* [13] carried out further experiments on the Pasminco lead circuit and demonstrated the ability of a modified prototype control valve to remotely close and open a 100 ton h^{-1} lead circuit using water as the coolant and induction heating to melt open the solidified plug.

EXPERIMENTAL

Figure 2 is a schematic diagram of the experimental apparatus. Most of the apparatus is contained inside an oven which keeps the equipment and the working fluid at a constant temperature. The only part of the apparatus outside the oven (the cold region in Fig. 2) are the heat exchanger and the pressure and tem-

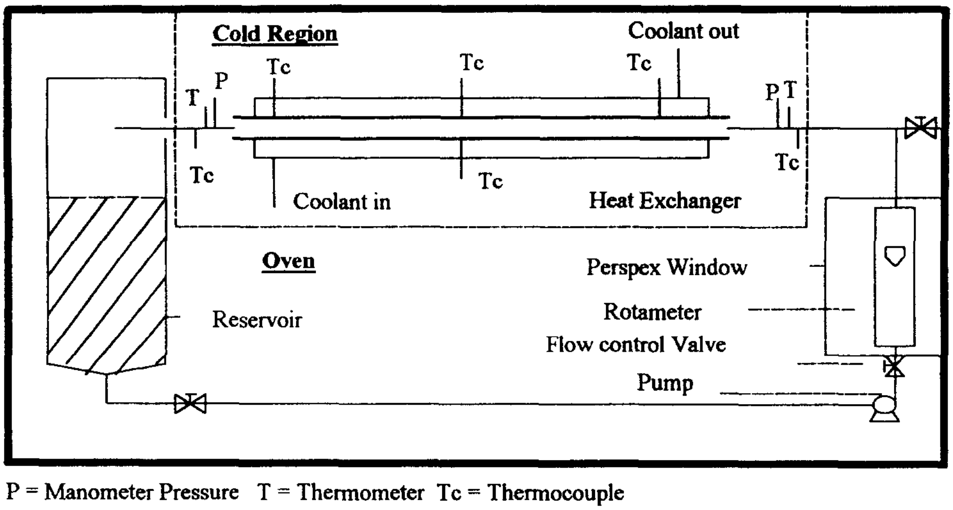

Fig. 2. Physical modelling experimental apparatus.

perature measurement instruments. The working fluid (eicosane) is kept in a 35 l reservoir and pumped through 1 in. diameter piping via a rotameter, the heat exchanger and back into the reservoir. The rotameter measures the flow rate entering the heat exchanger test section. The heat exchanger is cooled by water which is pumped through the shell and tube heat exchanger at 3 l min^{-1} at the required temperature from a constant temperature bath. From the rotameter top to the heat exchanger inlet there is a 200 mm calming section. The diameters of the heat exchangers used were 23, 17.5, 16.5 and 10.5 mm. The heat exchanger lengths were 440 mm for the 10.5 mm diameter and 455 mm for the others.

Temperature measurements were carried out using thermometers accurate to 0.1°C for molten eicosane and copper constantan thermocouples accurate to 0.5°C for the heat exchanger. The pressure drop across the heat exchanger was measured using specially designed piezometers. The piezometer consisted of a copper tube with a viewing slit cut on both sides of the copper tube which was sheathed with a clear plastic tube, to prevent the eicosane wax from leaking and had a light source placed behind it so as to enable the eicosane head level to be seen.

Experimental investigation of flow of a molten liquid through a subcooled tube can either be carried out under a constant pressure driving force or under a constant flow rate condition. In most previous work in this area, a constant pressure driving force was maintained. In this work constant flow rate condition permits experiments to be carried out very close to the point where tube blockage sets in. In the present study the subcooling was held constant while the flow rate was varied. The constant flow condition was achieved by manual adjustment of the rotameter.

The present investigation was motivated by the desire to model and control the flow of molten slag in a taphole. The working fluid was chosen to meet at least approximately dynamic, kinematic and thermal similarity of slag in a taphole as well as having accurately known relevant temperature dependent thermophysical properties. The relevant dimensionless groups chosen were Prandtl number, Reynolds number, dimensionless freezing parameter and Peclet number (see Table 1). The values of these dimensionless groups of the experimental apparatus and in a typical taphole are shown in Table 1. For convenience of experimentation, the working fluid should have a low melting point. The above conditions were satisfied by eicosane, a C20 alkane which has a single melting point at 36.45°C. At a Reynolds number of

Table 1. Dimensional and dimensionless parameters for slag and eicosane

Dimensional parameters	Slag 55.1% FeO 1.2% Fe_2O_3 34.6% SiO_2 9.1% CaO	Eicosane	Dimensionless parameters	Slag 55.1% FeO 1.2% Fe_2O_3 34.6% SiO_2 9.1% CaO	Eicosane
L [m]	0.3	0.3	L/D	12–37.5	8–12
D [mm]	25–38	8–25	Pr	124	70–50
To [K]	1473–1673	315–343	Re	40–615	31–1572
Tw [k]	573–1273	263–303	Pe	5000–76 000	2733–113 667
H [cm]	10–50	2–20	P*	6.56E5–3.28E6	6.8E6–6.63E7
M [tons h^{-1}]	1–10	0.001–0.5	Tw*	0.9–16	0.5–20

946 and L/D of 41.9, the uncertainties are Re 9.1%, P^* 3.5% and Tw^* 7.5%. A full error analysis is given by Pitsillos [10].

The following are the experimental steps used for each length to diameter ratio heat exchanger:

(1) select the degree of supercooling;
(2) sweep through a range of flow rates;
(3) record the pressure drop at each flow rate;
(4) under some cases samples were taken by ejection of the liquid eicosane using compressed air;
(5) repeat for next degree of subcooling.

In each experimental run the degree of cooling was adjusted by manipulating the coolant temperature. The working fluid was then allowed to reach thermal equilibrium. During this process the manual valve upstream of the cooling section was continuously adjusted in order to ensure the flow rate of the working fluid was maintained at the specified constant value. The size of the flow diameter at the exit of the heat exchanger is verified by some crust samples taken by ejection of the liquid eicosane out of the tube at the end of an experiment using compressed air.

RESULTS AND DISCUSSION

The raw experimental data of flow rate vs pressure drop were converted into a plot of dimensionless pressure drop (P^*) vs dimensionless flow rate (Re). They are presented in Figs. 3–5 for different degrees of subcooling (Tw^*) and pipe geometries (L/D). Raw data was also non-dimensionalised and presented on design curves of Tw^* vs Re and L/D vs Re for different pressure drops (P^*) in Figs. 6 and 7. For comparison the theoretical predictions based on the Zerkle and Sunderland (Z and S) model are shown as solid lines in Figs. 3–7. Following Z and S all solid properties were evaluated at $(T_f+T_w)/2$ while the liquid properties were evaluated at $[(T_o+T_e)/2+T_f]/2$.

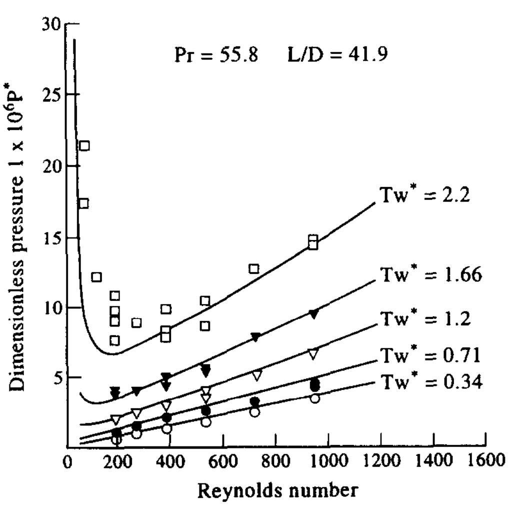

Fig. 3. Dimensionless pressure vs Reynolds number for $L/D = 41.9$.

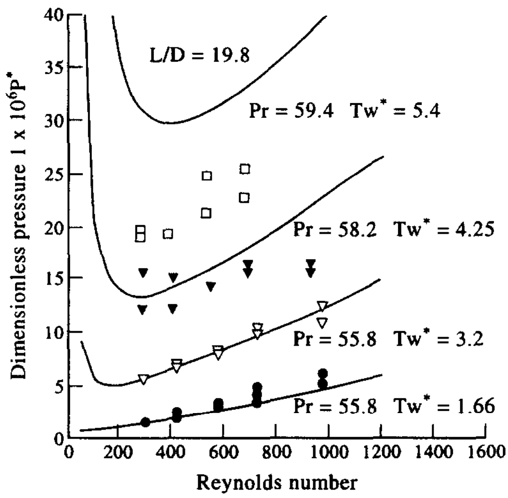

Fig. 4. Dimensionless pressure vs Reynolds number of $L/D = 19.8$.

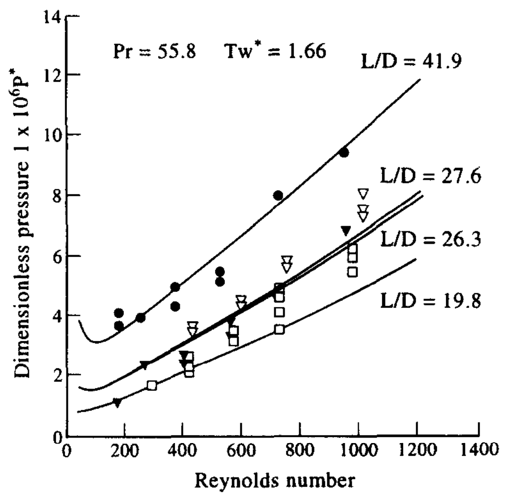

Fig. 5. Dimensionless pressure vs Reynolds number of various L/D.

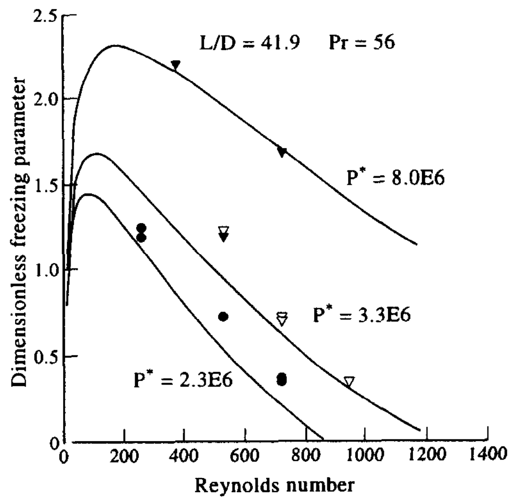

Fig. 6. Dimensionless freezing parameter vs Reynolds number for $L/D = 41.9$.

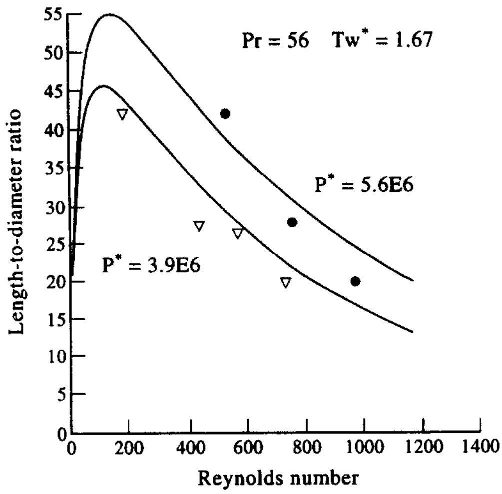

Fig. 7. Length-to-diameter ratio vs Reynolds number for $Tw^* = 1.67$.

Figure 3 is plot of dimensionless pressure drop (P^*) vs Reynolds number for a length to diameter ratio (L/D) of 41.9 and a Prandtl number (Pr) of 55.8. On each curve Tw^* is kept constant. The range of Tw^* covered is 0.34–2.2 ($Tw^* = 0$ corresponds to no freezing). The solid lines are the Zerkle and Sunderland predictions for the various dimensionless freezing parameters (Tw^*). The most interesting feature of this plot is the minimum exhibited by P^*. Above the minimum the increase in P^* with increase in Re is the usual phenomenon associated with laminar flow in pipes. Below the minimum point the theory predicts that there is an increase in pressure associated with a decrease in flow rate. The explanation for this is that the reduction of flow rate is accompanied by a large increase in crust thickness inside the tube and thus an increase in pressure drop. The numerical results of Pitsillos *et al.* [5] and Yeow *et al.* [14] also predicted this minimum in pressure drop. It can be shown that a curve of increasing pressure drop with decreasing flow rate is inherently unstable and physically not observable for a constant pressure system. For the experimental runs where the working fluid flow rate was below the minimum point predicted by theory in Fig. 3, an interesting phenomenon was observed. It was found that at these flow rates, the pressure drop is very sensitive to small fluctuations inflow rate. More frequent interventions were needed to keep the flow rate constant. It also took longer for the system to settle down to allow experimental data to be taken. This can be taken as an indication that below the minimum point the flow is unstable. If constant pressure is maintained it is likely that the tube will freeze shut.

Figure 4 is a similar plot of dimensionless pressure drop versus Reynold number for a length to diameter ratio of 19.8 and Prandtl number of 59.4. Experiments carried out showed that for a Prandtl number of 57, a 5% variation had an insignificant effect on flow rate. Therefore, a Prandtl number range of 55.8–59.4 will not influence the flow rate results. The results are in good agreement with the theory for a dimensionless freezing parameter (Tw^*) less than 4. For $Tw^* > 4$ the experimental pressure drop is about 50% lower than the Zerkle and Sunderland predictions. This can be a consequence of the breaking down of laminar flow or the formation of an air gap between the heat exchanger tube wall and the solid crust. An air gap introduces a resistance to heat transfer and, therefore, a smaller crust build-up occurs in the cooled section and, consequently, results in a lower pressure drop along the heat exchanger.

The phenomenon of solidification with fluid flow in transition and turbulent flows causing wavy interfaces has been observed in ice–water systems. The change from laminar to turbulent flow will increase the heat transfer between the fluid and the solid and as a result the crust thickness of the solidified layer inside the tube is decreased. Under certain conditions the solid–liquid interface formed may be wavy. The wavy interface is cased by different flow regimes along the length of the tube. The mathematical model indicates that the flow diameter at the exit of the heat exchanger is not small enough to cause the local Reynolds number to be in the transition or turbulent region. The size of the flow diameter at the exit of the heat exchanger is verified by some crust samples taken by ejection of the liquid eicosane out of the tube at the end of an experiment using compressed air. When the flow regime is turbulent or transitional there is an expansion while for the laminar regime the available channel for fluid flow contracts. This phenomena has previously been reported by Hirata [15], Giplin [16] and Toda [17] for the case of water–ice wavy interfaces. Toda *et al.* [17] reported that for an ice–water system $Tw^* > 2$ leads to wavy interfaces in a water–ice system. Wavy interfaces for a C18 alkane [2*n*-octadecane] have been reported by Myrum and Thumma [18]. Their experiments were for turbulent flow and $Tw^* > 5.4$ and the results verified the water–ice steady-state ice band correlation of Hirata *et al.* [15] for alkanes. Therefore, we would expect to observe wavy interfaces at $Tw^* > 2$ if the inlet flow regime and the length to diameter ratio of the tube did not effect the conditions under which ice bands occur. It should be noted that the ice–water studies and the *n*-octadecane study were in turbulent flow while our study is in laminar flow.

Figures 3 and 4 show that as Tw^* increases the corresponding crust thickness increases causing the P^* vs Re curve to shift upwards. Figure 5 shows the effect of length-to-diameter ratio on the P^* vs Re curve for a Tw^* of 1.66 and Pr of 55.8. The results indicate that doubling the L/D ratio more than doubles P^* for a fixed Reynolds number and dimensionless freezing parameter because the crust thickness increases with axial distance and, therefore, an additional tube length provides greater pressure drop than the previous length.

Figure 6 shows some of the results on a dimensionless freezing parameter vs Reynolds numbers curves for L/D of 41.9, Pr of 56.0 and various P^*. This representation of the results can be thought of as a horizontal slice of Fig. 3 at P^* of 2.3E6, 3.3E6 and 8.0E6. In order to control the flow rate of a molten liquid using solidification with fluid flow the only dimensionless group that can be controlled is Tw^*. The maximum exhibited is regarded as the maximum amount of subcooling required for a constant pressure system to reach total tube blockage. The experiments are shown to be in good agreement with theory. The results shown in Fig. 6 have flow rate control operational implications. Once the L/D has been chosen for the required operating pressure drop (P^*) and flow rate range (Re) then the only parameter that can deliver the variation of flow under controlled conditions is the dimensionless freezing parameter. Therefore, a plot similar to Fig. 6 for a given system is required to evaluate what variation in Tw^* is needed in order to control the flow rate within the required flow rate range. In other words it indicates how subcooling is used to control flow rate.

Figure 7 is a plot of length to diameter ratio vs Reynolds number for a Pr of 56 and Tw^* of 1.67 and P^* of 3.9E6 and 5.6E6. It shows the effect of changing the tube length on flow rate control. The results are in good agreement with theory. The results have certain design implications for flow rate control using crust formation. Once the maximum dimensionless freezing parameter and the operation pressure (P^*) are chosen then a similar plot to Fig. 7 can be used to choose the L/D that will provide the minimum required flow rate (blockage). The minimum cooling rate is used to obtain the maximum molten liquid flow rate while the maximum cooling enables the system to block shut.

When designing a flow rate control taphole the following steps need to be followed:

(1) determine the furnace operation head, operational temperature and slag properties;
(2) choose a taphole diameter ((1) and (2) defines P^*);
(3) determine from the cooling system available the range of coolant temperature (this determines operating Tw^* range);
(4) using a curve similar to Fig. 7 select the L/D (around 5–10) that will enable operation over the flow rate range required. If it is not feasible choose another taphole diameter and repeat steps;
(5) one the L/D has been chosen, a curve similar to Fig. 6 can be drawn to show how the varying of the subcooling will be used to control the flow rate.

CONCLUSION

The experimentally measured pressure vs flow rate data and for different dimensionless freezing parameter (Tw^*) were found to be in reasonable agreement with that predicted by the Zerkle and Sunderland model. The experiments were carried out for $100 < Re < 1000$, $0.3 < Tw^* < 5.4$ and for control section length to diameter ratios (L/D) of 41.9, 27.6, 26.3 and 19.8. The experimental working fluid used was eicosane because it has a fixed melting point, the exact temperature dependent properties are known and it simulates high temperature slags. For $Tw^* < 4$ the agreement between experiment and theory is very good and is within 20%. The length-to-diameter ratio vs Reynolds number curve can be used for taphole analysis and design. The dimensionless freezing parameter vs Reynolds number curve demonstrates how the flow rate is controlled by varying the dimensionless freezing parameter for a constant pressure system. The maximum exhibited indicates the maximum subcooling required for tube blockage to come about. For $Tw^* > 4$ it is clearly observed that the experimental results are significantly lower than the theoretical predictions and may be attributed either to the laminar flow assumption breaking down or the possible existence of an air gap. Further experimental investigation is required to establish the exact condition where the laminar flow model breaks down or an air gap forms and obtain information on when stable ice-bands form. The model has been sufficiently verified to be used for the design of control systems for transport of molten liquids in laminar flow.

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REFERENCES

1. Epstein, M. and Cheung, F. B., Complex freezing–melting interfaces in fluid flow. *Annual Review Fluid Mechanics*, 1983, **15**, 293–319.
2. Cheung, F. B. and Epstein, M., Solidification and melting in fluid flow. *Advances in Transport Processes*, Vol. 3, ed. A. S. Mujumdar and R. A. Mashelkar. Wiley, New York, 1984.
3. Fusako, S. and Seki, N., Freezing and melting characteristics in internal flow. *Proceedings of the International Symposium on Cold Regions Heat Transfer*, ASME, Alberta, Canada, 1987, pp. 25–38.
4. Zerkle, R. D. and Sunderland, J. E., The effect of liquid solidification in a tube upon laminar-flow heat transfer and pressure drop. *Journal of Heat Transfer*, 1968 **90**, 183–190.
5. Pitsillos, J. S., Seeling, C., Yeow, Y. L. and Gray, N. B., Solidification of molten liquids in laminar flow in a tube. *CHEMECA*, 1989, 914–921.
6. Pitsillos, J. S. and Gray, N. B., Handling of slags leaving metallurgical vessels. *Proceedings of the EPD Congress*, ed. D. R. Gaskell. TMS, 1991, pp. 279–293.
7. Pitsillos, J. S. and Gray, N. B., A high temperature control valve for molten liquid furnace products. *Proceedings of the Mervyn Willis Symposium and Smelting Refining Course*, University of Melbourne, 1992, pp. 31.1–31.11.
8. Australian Patent no. 653004, Regulation of flow rate of liquid furnace products.

9. United States Patent no. 5406969, Regulation of flow rate of liquid furnace products.
10. Pitsillos, J. S., Modelling of phase change with fluid flow—flow rate control of molten liquids. Ph.D. thesis, University of Melbourne, Department of Chemical Engineering, Melbourne, Australia, 1992.
11. Harris, J. A., Stewart, A. J. and Gray, N. B., A novel control valve for molten materials. *The 6th Asian Congress of Fluid Mechanics*, Singapore, 1995, pp. 857–860.
12. Stewart, A. J., Harris, J. A. and Gray, N. B., A prototype control valve for molten metals. *Pyrometallurgy* '95, Cambridge, U.K. 1995, pp. 347–357.
13. Pitsillos, J. S., Berrigan, T., Kyllo, A., Harris, J. and Gray, N. B., Pilot plant trial of prototype control valve for molten metals with flow establishment and stoppage features at Pasminco Research Centre, Newcastle. G. K. Williams CRC for Extractive Metallurgy, Report no. 95/13, The University of Melbourne, 1995.
14. Yeow, Y. L., Gethin, D. T. and Lewis, R. W., Solidification at the entrance to a subcooled tube. *Industrial and Engineering Chemistry Research*, 1990, **29,** 896–901.
15. Giplin, R. R., Ice formation in a pipe containing flows in the transition and turbulent regimes. *Journal of Heat Transfer*, 1981, **103,** 363–368.
16 Hirata, T. and Matsuzawa, H., A study of ice-formation phenomena on freezing of flowing water in a pipe. *Journal of Heat Transfer*, 1987, **109,** 965–970.
17. Toda, S., Sugiyama, H., Owada, H., Kurokawa, M. and Hori, Y., Laminar flow heat transfer in a tube with internal solidification. *Proceedings of the 8th International Heat Transfer Conference*, 1986, pp. 745–1750.
18. Myrum, T. A. and Thumma, S., Freezing of a paraffin flow downstream of an abrupt expansion. *International Journal of Heat and Mass Transfer*, 1992, **35**(2), 421–431.