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EXPERIMENTS ON HEAT TRANSFER AND PRESSURE DROP IN A HORIZONTAL TUBE WITH INTERNAL SOLIDIFICATION

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Abstract—The results of a series of experiments on liquid solidification in the thermal entrance region of a horizontal tube are presented. All involved steady, hydrodynamically developed laminar flow with a steady-state frozen deposit at the inside wall, a constant and uniform wall temperature, and a Graetz number in a range of significant natural convection. Heat transfer and pressure drop data is presented to further define the influence of free convection on solidification. It is shown that Oliver's correlation of combined forced and free convection is applicable when the L/D is significantly greater than 50, and that the correlation is more accurate when corrected for the presence of a solid phase thickness. It is also shown that a parabolic velocity profile should not be used in the analytical prediction of pressure drop when natural convection effects are included. The results of these experiments confirm and strengthen previously reported data and conclusions.

NOMENCLATURE

D, I.D. of tube;
k_s, thermal conductivity of solid phase;
k_l, thermal conductivity of liquid phase;
L, length of test section;
$\dot{m}$, mass flow rate;
P_0, inlet pressure;
P_e, exit pressure;
T_e, exit temperature [°F];
T_f, freezing temperature [°F];
T_0, inlet temperature [°F];
T_w, tube wall temperature [°F];
$\bar{T}_b$, $(T_0+T_e)/2$;
V, mean inlet velocity;
α, thermal diffusivity of liquid;
β, coefficient of thermal expansion;
δ, radius of solid phase interface;
μ_w, dynamic viscosity at [32°F];
μ_b, dynamic viscosity at mean bulk temperature;
ν, kinematic viscosity;
δ^*, $2\delta/D$;
P^*, $(P_0-P_e)/(\rho V^2/2)$;
q^*, $(T_0-T_e)/(T_0-T_f)$;
T_w^*, $k_s(T_f-T_w)/k_l(T_0-T_f)$;
z^*, $4/Gz$;
Gr, Grashof number, $g\beta(\bar{T}_b-T_f)D^3/\nu^2$;
Gz, Graetz number, $Re.Pr.D/L$;
Nu, Nusselt number defined in equation (1);
Pr, Prandtl number, ν/α;
Re, Reynolds number, DV/ν;
$(Gr.Pr.L/D)_{corr}$, $(Gr.Pr.L/D)(\delta^*)^2$.

INTRODUCTION

SOLIDIFICATION processes are common in many engineering systems which involve fluid flow and heat transfer. Problems involving these melting and freezing processes are referred to as moving-boundary problems in heat-transfer theory and have been summarized by Muehlbauer and Sunderland [1], Boley [2] and Bankoff [3].

Those melting–freezing problems involving internal flow oftentimes become unusually troublesome, especially when natural convection is a significant superimposed mechanism. The importance of these internal problems was recognized very early by Brush [4] and some early one-dimensional solidification analyses of problems involving tube flow were presented by London and Seban [5], Poots [6] and Hirshburg [7]. In 1968, Zerkle and Sunderland [8] published an important analytical and experimental investigation of solidification in hydrodynamically developed tube flow under steady-state conditions. They were able to show that when hydrodynamic entrance effects and natural convection are not important and a laminar parabolic velocity profile assumed, the steady-state problem of forced convection in the thermal entrance of a tube with constant wall temperature and a smooth internal frozen shell reduces to the classical Graetz problem. Thus, the Nusselt number, Nu, and the dimensionless heat transfer, q^*, are dependent solely upon the tube Graetz number. For a given flow rate, the solid phase thickness can be computed from heat conduction theory and the pressure drop from laminar flow theory with the assumed parabolic velocity profile. Zerkle and Sunderland presented experimental data on the heat transfer and pressure drop which tended to confirm their parabolic profile analyses at large Graetz number (small z^*). However, at low Graetz number (large z^*) their data indicated a very strong and controlling natural convection effect which approximately doubles the heat transfer. A semi-empirical method was presented for taking this natural convection into account by using the empirical formulation developed by Oliver [9].

An experimental investigation of solidification in

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thermal entrance region flow was also carried out by Depew and Zenter [10] and yielded data which these authors believed to be somewhat more accurate than that of Zerkle and Sunderland, although confirming their general conclusions for small z^*. A much smaller diameter tube was used in these experiments and much of the data taken at large Graetz number. They showed convincingly that Oliver's natural convection correlation produces an underestimate of the heat-transfer coefficient when formulated with system dimensions and used for an L/D significantly less than 50. Their experiments utilized an L/D of 28·3 whereas L/D's of 19 and 53·75 were used in Zerkle and Sunderland's experiments. The large L/D experiments were shown to agree well with Oliver's correlation formed with system dimensions, although the spread of the data was large. Oliver himself suggested an L/D effect on natural convection in the range of L/D's from 50 to 70, but not much above this. Depew and Zenter also demonstrated that the pressure drop which occurs across a tube with an internal frozen deposit is extremely sensitive to variations in tube wall temperature. The wall temperatures in their experiments, however, were not sufficiently uniform to allow a quantitative comparison with the theoretically predicted pressure drop.

The results of the two studies above represent all that is known about the fundamental (unconstrained) relationships between heat transfer, pressure drop and steady-state flow rate in the thermal entrance region flow of a tube which is partially frozen. The determination of the conditions which will lead to freeze blockage in a tube such as this is an important one for a given flow system and is, essentially, a problem that is dependent upon the accuracy of the unconstrained relationships between pressure drop and flow rate and the manner in which the upstream and downstream systems constrain these relationships. Indeed, DesRuisseaux and Zerkle [11] used the results of [8] to show how this type of determination can be made for a given flow system.

The investigation presented here was, essentially, an experimental study of solidification in the thermal entrance region of a tube under steady-state conditions and constant wall temperature and utilizes the theory developed by Zerkle and Sunderland as a comparison. The experiments were similar to those of [8] and [10], although conducted under different conditions and with a tube of smaller I.D. The objective of the investigation was to confirm the data of these previous experiments, particularly in the low Graetz number range where Zerkle and Sunderland's data exists alone. Also, the experiments were to develop data which could be used to explain some of the mechanisms of the process which are not yet clearly understood. In particular, the role which L/D plays in influencing the natural convection is still not clear. That is, it is not known to what extent Oliver's correlation can be used in solidification problems when the correlation is formulated with system dimensions rather than actual internal dimensions. All that exists is the suggestion that it isn't good for L/D less than 50 and it is good for L/D in the neighborhood of 50, the latter conclusion resulting from an interpretation of a single set of data. In solidification problems, however, the actual ratio cannot be controlled as it depends on the local thickness of the solid phase which in turn depends upon other system parameters. One objective of the experiments described here, therefore, was to produce data for one L/D which is significantly greater than 50 and a range of other conditions which influence the solid phase thickness, thus producing a spread of data comparable to the large L/D results of Zerkle and Sunderland and sufficient to check the usage of Oliver's correlation for L/D values greater than 50.

Another important objective of the experiments was to produce additional data on the pressure drop which occurs across a tube with an internal frozen deposit. The flattening of the velocity profile by the converging flow should considerably increase the pressure drop above that predicted by the Graetz theory even though the heat transfer is relatively insensitive to the velocity profile. Any roughness at the liquid–solid interface should add to the increase. Natural convection, however, tends to reduce the solid phase thickness and correspondingly, reduces the pressure drop for all but the very small Graetz numbers. Even though these mechanisms are difficult to study individually, their net effect would be to cause a deviation from the theoretical. The objective of the experiments, therefore, was to produce pressure drop data sufficiently accurate to allow this comparison with the theory.

EXPERIMENTAL APPARATUS

Experiments were made with an apparatus in which water was used as the freezing medium. It consisted of a closed water circulation and temperature control system and a test section cooling system, with instrumentation for the measurement and recording of temperatures, pressures and flow rate. A schematic of the apparatus is shown in Fig. 1.

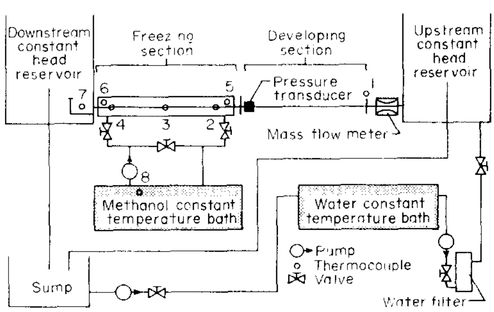

FIG. 1. Schematic of apparatus.

The water circulation system was composed of inlet and exit constant head reservoirs, an entrance section of length 67·375 in, a test section 45·656 in in length, and a constant temperature bath and circulating pump. Both the entrance and test section were continuous and constructed of thin wall copper tubing, 0·570 in in I.D. The constant temperature bath and inlet reser-

Table 1. Experimental data and computed results

Run	$\dot{m}$ (lbm/min)	T_0	T_e	T_w	$\bar{T}_b$	Re	$Z^*(10)^2$	T_w^*	$(Gr.Pr.L/D)$	$(Gr.Pr.L/D)_{corr}$	q^*	Nu	p^*
1	2·16	65	51·5	24·9	58·3	1359	3·48	0·860	$2·99(10)^8$	$2·13(10)^8$	0·409	14·75	28·0
2	1·62	65	50·3	24·9	57·6	1018	4·72	0·860	2·76	1·87	0·446	12·20	46·5
3	1·18	65	46·4	24·9	55·7	740	6·66	0·860	2·30	1·31	0·562	11·75	101
4	1·46	65	49·6	22·3	57·3	918	5·23	1·173	2·72	1·52	0·467	11·60	104
5	1·27	65	44·8	25·1	54·9	799	6·24	0·83	2·06	1·25	0·613	14·15	70·7
6	2·44	65	53·7	22·3	59·3	1537	3·05	1·173	3·42	2·27	0·343	13·60	33·4
7	2·73	65	52·8	24·1	58·9	1720	2·72	0·962	3·20	2·39	0·370	16·70	22·6
8	1·49	65	49·4	24·2	57·2	938	4·85	0·939	2·74	1·80	0·474	12·80	62·2
9	1·29	65	45·0	25·2	55·0	813	6·13	0·824	2·24	1·36	0·606	14·20	120
10	0·76	65	40·8	32·0	52·9	480	9·20	0	1·81	1·81	0·734	12·60	—

voir were of sufficient capacity and had a control which allowed the setting of inlet temperature with no noticeable fluctuation. The entrance section of the tube as well as the external side of the test section were well insulated and the circulating water filtered to eliminate algae and particulates. The L/D for the entrance and the test section were 118 and 80·1, respectively.

A counter flow forced circulation cooling system using methanol as coolant was employed to control the tube wall temperature in the test section by circulating the methanol in the cooling jacket of the test section. A constant temperature bath and reservoir was used to control and maintain the coolant temperature, and this was done with no noticeable fluctuation. Methanol was used as a coolant because of its low viscosity at low temperatures, and a 1/2 hp pump used to circulate the methanol at a flow rate sufficient to insure a negligible difference in methanol temperature entering and leaving the test section. Great care was taken in the design of the test section and in the conduct of the experiments to insure that the maximum non-uniformity in tube wall temperature was within 1°F. Oftentimes, the variation was much less than this.

A hot-wire anemometer type flow meter was used to sense the flow rate and a thermocouple at location 1 used to insure no alterations in inlet temperature. The flow meter was calibrated with weighed samples within 2 per cent. The test section inlet pressure was measured using a diaphragm type strain gauge transducer that was calibrated to 0·01 in of water. Thermocouples were peened into the tube wall at each end and the middle of the test section, at locations 2, 3 and 4 in Fig. 1, to accurately measure the uniformity of wall temperature. The exit mean temperature was measured by a thermocouple located in a small plastic mixing cup at the exit of the tube, location 7. The mixing cup was designed to trap and mix fluid issuing from the tube yet allow the exit reservoir to impose the prescribed exit static pressure. All of these measurements were recorded continuously. The system was leveled with a surveying transit so that each point along the axis of the entrance and test section was at the same elevation within 1/64 in. The head height of the constant head reservoirs at inlet and exit was measured to within 0·01 in with a cathetometer. All thermocouples were calibrated with NBS certified thermometers.

RESULTS

The results of the experiments are shown in the table along with some pertinent quantities which were computed from the data. In all experiments, the inlet temperature was maintained at 65°F and the exit static pressure at 3·02 in of water. The tube wall temperature and upstream reservoir height (flow rate) were the parameters which were varied in the experiments. The heat transfer q^* was evaluated directly as a temperature ratio and $z^*(=4/Gz)$ evaluated from the Reynolds number, Re, Prandtl number, Pr, and test section L/D. All properties were evaluated at the arithmetic average of the inlet and exit bulk temperatures. The Nusselt number, Nu, is based on an arithmetic mean of inlet and exit temperatures instead of the more usual logarithmic mean and is computed from

$$Nu = 2\,.\,q^*/(2-q^*)\,.\,z^*. \tag{1}$$

The arithmetic mean is used to facilitate a comparison with the results of [8–10]. In computing both the Nusselt number and the Grashof number, Gr, the effective wall temperature was taken as 32°F. In order to see the effects of the solid phase thickness and correspondingly the actual inside diameter of the channel on the natural convection correlation developed by Oliver, that is

$$Nu = 1·75(\mu_w/\mu_b)^{0·14}[\pi/z^* + 5·64(10)^{-4} \times (Gr\,.\,Pr\,.\,L/D)^{0·7}]^{1/3} \tag{2}$$

it is necessary to correct the grouping $Gr.Pr.L/D$ by multiplying by the square of the dimensionless solid–liquid interface radius. This quantity was estimated from the empirical theory of Zerkle and Sunderland, for the conditions of these experiments, and used as a multiplicative correction to $Gr.Pr.L/D$. The values of the corrected as well as uncorrected groupings are shown in the table.

The computed Nusselt number is plotted in Fig. 2 to facilitate a comparison with equation (2). Computed values from [8, 10] are also shown. Heat-transfer data is plotted in Fig. 3, along with that of [8, 10], to illustrate its relationship with the Graetz theory.

The pressure drop data is shown in Fig. 4 and compared with the results of [8, 10]. The theoretically predicted pressure drop is taken from [8] and is based on the liquid–solid interface radius computed from the

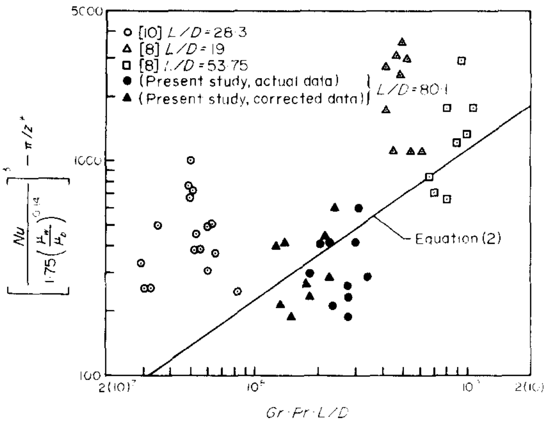

FIG. 2. Comparison of heat-transfer data and Oliver's correlation.

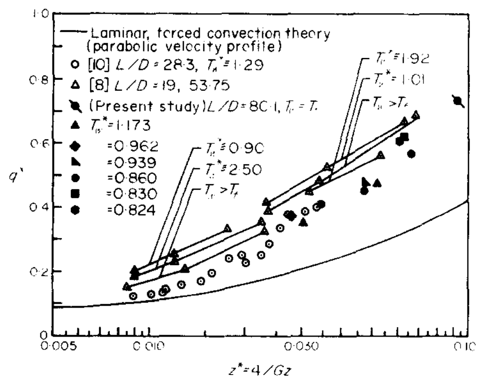

FIG. 3. Comparison of heat-transfer data and Graetz theory.

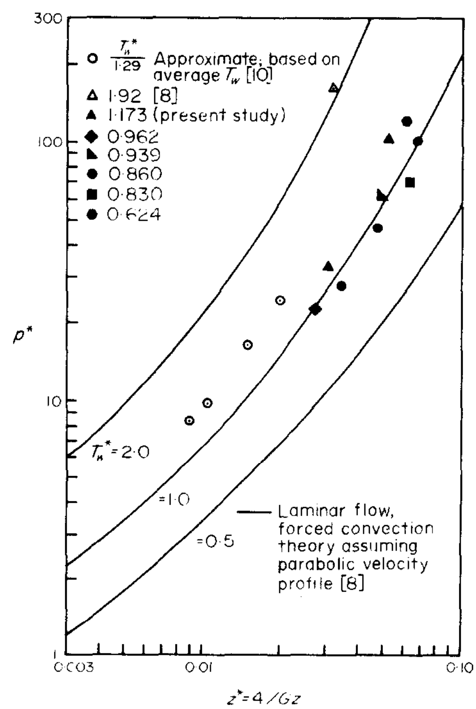

FIG. 4. Comparison of pressure drop data and laminar flow–Graetz theory predictions.

Graetz theory and the pressure drop computed from laminar flow theory utilizing a parabolic velocity profile.

Two extremely important processes were observed in the experiments which are now believed to be fundamentally important in the design of any solidification experiments and therefore worth mentioning here along with the results. The first is the very long time required for the experiments to reach steady state and the possible error incurred in the results by not allowing the process to reach a true steady condition. Continuous recordings of flow rate and exit bulk temperature were made to avoid stopping an experiment prematurely. Several sets of data, however, had to be discarded before the very gradual drift in readings were noted and found to be significant.

A second characteristic of the solidification process which was also surprisingly found to be very important is the supercooling in the liquid phase which occurs initially upon reduction of the wall temperature. The exit bulk temperature would initially decrease below that which was expected and, after a time, would increase abruptly coincidentally with an increase in pressure drop. This spontaneous onset of freezing seemed random and was oftentimes very pronounced, although when the wall temperature was not much below 32°F it was not so obvious and sometimes did not occur at all; that is, the liquid remained in a supercooled state and the only reduction in flow rate was that associated with the increased viscosity. This occurred despite accumulated particulates, vibration and roughing the inside surface of the tube. When the wall temperature was below 27°F, little supercooling was noted with the solidification process beginning almost immediately. The only solidification data appearing in the tabulation, therefore, are those runs which were obviously free from supercooling effects and, consequently, have wall temperatures below 27°F.

DISCUSSION

The presence of the internal ice layer and the fact that the I.D. of the tube is different from D and that the actual length-to-diameter ratio may be much greater than L/D is sometimes forgotten when viewing the dimensionless groupings which have been considered. The quantity z^* is actually independent of whether its formulaton is on a system basis or an internal basis. That is, it is numerically the same when formulated using the solid phase interface radius and actual local velocity as it is when formulated using the tube I.D. and inlet velocity. Thus, with the result of the Graetz theory that q^* is a function only of z^*, it is seen that z^* evaluated from system conditions yields the forced convection heat transfer without the necessity of considering the internal freezing characteristics, even though the wall temperature is below the freezing temperature of the liquid phase. All that is necessary is the flow rate. The same conclusion applies to the Nusselt number, Nu, which is functionally related to q^* through equation (1).

When natural convection effects are present, the q^*, either measured or predicted, will necessarily become a function of the additional variable $Gr.Pr.L/D$. When this grouping is formulated on the basis of the actual I.D. instead of the tube I.D., it is clear that its magnitude is dependent upon the thickness of the solid phase and therefore not invariant to formulation as is the case of z^*, and Nu. That is, even though $Gr.Pr.L/D$ may be a computed value, its actual value will be different. Therefore, it has been suggested that in order to properly correlate solidification data involving natural convection the quantity $Gr.Pr.L/D$, based on system dimensions, must be corrected to internal local conditions by multiplying by the square of the dimensionless interface radius. The corrected values of this grouping have been included in the tabulation for this reason. Thus, any system condition such as inlet liquid temperature or tube wall temperature which has an effect on the solid phase thickness, will make itself felt on the natural convection by way of the correction of $Gr.Pr.L/D$.

Heat-transfer data is presented in Fig. 2 in a way consistent with the traditional presentation of empirical data on combined forced and natural convection. The grouping $Gr.Pr.L/D$ is corrected as well as uncorrected. Uncorrected data fall within the deviation range of the correlation, indicating Oliver's correlation will predict the Nusselt number within its accuracy of ± 20 per cent when formulated directly with system dimensions. This was suggested for an L/D of 50, a suggestion which now appears correct and also true for an L/D as high as 80, and probably higher as Oliver has suggested little L/D effect above 70. This is not to say that the presence of the solid phase has no effect on the convection process, only that the magnitude of the effect is not significant in the use of Oliver's correlation. The uncorrected data is actually significantly lower, with the Nusselt numbers approximately 5–10 per cent below those predicted by the correlation. The corrected data is seen to be in excellent agreement with the correlation, actually in better agreement than the data originally used in the development of the correlation. Thus, when used for an L/D greater than 50, Oliver's correlation is thought to slightly overestimate the Nusselt number when it is formulated with system dimensions and provides a very accurate prediction of the Nusselt number when formulated with internal dimensions. It may also be more accurate than the spread of data used in its development suggests.

It is seen in Fig. 3 that the heat transfer measurements agree well with those of [8, 10], although the conditions were somewhat different. The heat-transfer data of [8] displays the same behavior pattern as observed in the present experiments in which supercooling was noted. That is, as the wall temperature is lowered somewhat below 32°F, the heat transfer first increases and subsequently decreases with a further reduction in wall temperature. This characteristic is believed due to the enhanced natural convection which occurs when the liquid is supercooled at the tube wall and also to the increase in surface area due to the initial and probably spotty nucleation and solid phase growth. In the present experiments, wall temperatures as low as 27°F had to be reached to eliminate this behavior. Thus, it is believed that the data from the low temperature run of [8] is more appropriate for comparison. It can be seen in the figure that q^* is essentially a function only of z^*, even though natural convection is involved. The natural convection is seen to have a very uniform influence on the q^* vs z^* relationship with very little, if any, parametric dependence on $Gr.Pr.L/D$. This is a result of the functional dependence between $Gr.Pr.L/D$ and z^* which exists because of the presence of the melting–freezing process. The manner of data presentation in Fig. 2 presumes these variables to be independent. The additional data presented in Fig. 3 should be of value in the further development of semi-empirical formulations involving Oliver's correlation beyond that already presented by Zerkle and Sunderland.

The pressure drop data presented in Fig. 4 was unexpected and therefore repeatedly verified. It is in remarkably close agreement with the pressure drop predicted using the solid phase interface radius of the Graetz theory along with the parabolic velocity profile and laminar flow theory. One data point from [8] is shown and is slightly higher than the theory, although this is still thought to be in very satisfactory agreement. The data from [10] also appears to be in essential agreement with the theory when the wall temperature from this data is represented by an average value. The agreement with the theory is believed to be only coincidental, with the increased pressure drop caused by the converging flow being approximately balanced by the decrease in pressure drop caused by the natural convection. In all experiments, the solid phase interface appeared to be very smooth and regular. Thus, surface roughness is not thought to be a pertinent factor. An important suggestion from a predictive standpoint, therefore, is that natural convection and converging flow effects are approximately cancelling phenomena and that satisfactory predictions of pressure drop appear obtainable from the Graetz theory and a laminar flow analysis, even though predictions of heat transfer will be greatly in error. The extent to which this is true, however, can only be determined after much more extensive data is presented. From a mechanistic and somewhat more fundamental standpoint, however, it is believed that the data indicate the fallacy in the use of parabolic velocity profile for pressure drop calculations and the correctness of including natural convection effects in establishing the radius of the solid phase interface.

CONCLUSIONS

The specific conclusions of the experimentations and examination of the data developed in this investigation are as follows:

1. Liquid phase supercooling is unavoidable in internal solidification studies of filtered tap water and does not seem to be influenced by the presence of additional particulates in the liquid, tube surface roughness beyond that of a "smooth" tube, or vibration beyond that which is normally encountered.

2. Oliver's correlation for combined free and forced convection in laminar flow in tubes will predict the Nusselt number just as accurately even when a frozen shell exists on the inside tube wall so long as the $L/D \geqslant 50$, with no apparent upper limitation on L/D. The accuracy of this prediction is ± 20 per cent and according to the data of this study it is likely to be somewhat on the high side. The data also show that Oliver's correlation very accurately predicts the Nusselt number for the case of flow with an internal frozen shell when it is formulated with actual internal dimensions, suggesting that Oliver's correlation may be somewhat more accurate than the cited ± 20 per cent.

3. The heat-transfer data is in essential agreement with that of Zerkle and Sunderland in the large z^* range where the later data previously existed alone. The conditions of the experiments were quite different, suggesting that a simple $q^*(z^*)$ relationship exists within typical experimental error.

4. The pressure drop data suggests that in the range of z^* where natural convection effects are significant, a parabolic velocity profile cannot be used with laminar flow theory to predict pressure drop. The underestimate in this procedure is of the order of the overestimate in neglecting natural convection effects altogether. The data was found to agree well with the theory of Zerkle and Sunderland wherein both assumptions are made.

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EXPERIENCES SUR LE TRANSFERT THERMIQUE ET LA PERTE DE CHARGE DANS UN TUBE HORIZONTAL AVEC SOLIDIFICATION INTERNE

Résumé—On présente les résultats d'une série d'expériences sur la solidification d'un liquide dans la région d'établissement du régime thermique à l'intérieur d'un tube horizontal. Toutes ces expériences supposent un écoulement laminaire établi permanent avec un dépôt congelé en état permanent sur la paroi interne, une température de paroi constante et uniforme, et un nombre de Graetz situé dans le domaine d'une convection naturelle importante. Les données de transfert thermique et de chute de pression sont présentées afin de définir plus avant l'influence de la convection libre sur la solidification. On montre que la corrélation d'Oliver pour la convection mixte est applicable lorsque L/D est nettement supérieur à 50, et que cette corrélation est plus précise lorsqu'elle est corrigée afin de tenir compte de l'épaisseur de la phase solide. On montre également, qu'un profil de vitesse parabolique ne doit pas être utilisé dans la prévision analytique de la chute de pression lorsque sont inclus les effets de convection naturelle. Les résultats de ces expériences confirment et consolident les données et les conclusions présentées antérieurement.

UNTERSUCHUNGEN DES WÄRMEÜBERGANGS UND DRUCKABFALLS IN EINEM WAAGERECHTEN ROHR MIT INNERER ERSTARRUNG

Zusammenfassung—Es werden die Ergebnisse einer experimentallen Untersuchung über die Erstarrung im thermischen Einlaufbereich eines waagerechten Rohres wiedergegeben. Zugrundegelegt ist eine stationäre, hydrodynamisch ausgebildete, laminare Strömung mit einem stationär erstarrten Anteil an der Innenwand, eine konstante und einheitliche Wandtemperatur und eine Graetz-Zahl im Bereich der natürlichen Konvektion. Daten für den Wärmeübergang und den Druckabfall sind angegeben zur weiteren Klärung des Einflusses der freien Konvektion auf die Erstarrung. Es zeigte sich, daß die Korrelation von Oliver für kombinierte erzwungene und freie Konvektion anwendbar ist, wenn das Verhältnis L/D wesentlich größer als 50 ist. Die Korrelation erwies sich als genauer, wenn sie auf das Vorhandensein einer festen Phase bestimmter Dicke korrigiert wird. Es ergab sich auch, daß ein parabolisches Geschwindigkeitsprofil für die analytische Behandlung nicht benutzt werden soll, wenn Einflüsse der natürlichen Konvektion vorhanden sind. Die Ergebnisse dieser Experimente bestätigen und bekräftigen frühere Daten und Schlußfolgerungen.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ТЕПЛООБМЕНА И ПЕРЕПАДА ДАВЛЕНИЯ В ГОРИЗОНТАЛЬНОЙ ТРУБЕ С ВНУТРЕННИМ ЗАТВЕРДЕВАНИЕМ ЖИДКОСТИ

Аннотация — Приводятся результаты серии экспериментов по затвердеванию жидкости на тепловом входном участке горизонтальной трубы. Во всех экспериментах использовалось устойчивое, гидродинамически развитое ламинарное течение с устойчивым замерзшим осадком на внутренней стенке при постоянной и однородной температуре стенки и числах Грэтца для значительной естественной конвекции. Для определения влияния свободной конвекции на затвердевание приводятся данные по теплообмену и перепаду давления. Показано, что корреляция Оливера для совместной свободной и вынужденной конвекции применима при L/D значительно большим 50, и что с поправками на толщину твердой фазы корреляция более точная. Кроме того показано, что в аналитических расчетах перепада давления, когда учитываются эффекты естественной конвекции, параболический профиль скорости использовать не следует. Результаты этих экспериментов подтверждают и делают еще более достоверными ранее приводимые в литературе данные и выводы.