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Experimental evaluation of parameters affecting turbulent flow freeze blockage of a tube

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INTRODUCTION

THE FREEZING of a flowing liquid, as a result of external cooling of the walls of the tube or duct containing the flow, is a common occurrence. The effects of this internal solidification on heat transfer and pressure drop may be significant and, in fact, may alter the performance of a system to the point of being unsatisfactory. Agricultural irrigation networks and solar collector piping are examples of systems in which internal freezing may ultimately lead to complete failure. Thus, an understanding of the influence of various parameters on the freezing of a turbulent internal flow is of current interest.

Though many internal flow problems are turbulent in nature, the publication of data pertaining to the freezing of these flows has been limited. A steady-state analysis and experimental data were presented by Thomason *et al.* [1] in 1978, and transient results were published by Thomason and Mulligan in 1980 [2]. In 1981, Sampson and Gibson [3], using an approach similar to that of ref. [1], analyzed the problem of nozzle blockage by the freezing of a liquid metal in turbulent flow. In 1982 Epstein and Cheung [4] presented a simplified solution for the steady-state turbulent case with constant wall temperature, and used these results to predict pipe blockage.

During the experiments of refs. [1, 2], a freezing instability caused oscillations of test-section pressure drop and flow rate, and further verification of an instability in the ice layer was given by the experiments of Gilpin [5]. In 1985 Hirata and Ishihara [6] also reported flow oscillations during an experimental study of freeze blockage. They then developed a method of predicting blockage, assuming the existence of the ice-band structure reported by Gilpin [5]. This method and their experiments, however, covered a range of parameters essentially excluding the present study.

In an effort to gain further insight into the influence of selected parameters on pipe blockage by freezing of the internal turbulent flow, an experimental study was conducted. Specifically, the initial Reynolds number, external convective conditions, and the relationship of the upstream flow characteristics to those of the freezing section were varied during the experiments.

EXPERIMENTS

Experiments were conducted using a horizontal counterflow heat exchange apparatus employing two closed-loop, temperature-controlled fluid circulation systems, with water as the freezing medium in the tube. Methanol was used as the external coolant and was circulated through the shell side of the test section with a Reynolds number of approximately 40 000. The developing section was 188 cm long and had an inside diameter of 1.65 cm, yielding an L/D of 114. The tube was of the same material and diameter as the developing section, and had an L/D of 66. Otherwise, the system and procedure were similar to those used in the turbulent flow freezing experiments of Thomason and co-workers [1, 2].

Once a transient was started, the experiment was allowed to continue until the continuously monitored pressure at the test-section inlet indicated that a steady state had been reached, or that complete blockage had occurred, or until it appeared that the freezing process would never achieve either a steady state or complete blockage. Data were taken at several Reynolds numbers ranging from 4500 to slightly over 10 000, with the upper limit being dictated by the cooling system capacity. At each Reynolds number, transients were run at values of T^* selected to generate responses of all the types mentioned. Different flow restrictions were then placed in the inlet of the developing section and experiments were run at the same initial Reynolds number to determine the effect of upstream flow characteristics on the system freezing response.

RESULTS AND DISCUSSION

The data from these experiments are presented in Table 1, along with parameters computed from these data. A given transient is described as 'smooth' or 'oscillatory', with the final state being noted as steady, complete blockage, or continuous oscillation. The smooth response exhibited no apparent pressure drop instability throughout the transient, whereas in the oscillatory response the pressure drop oscillated unpredictably or, in some cases, periodically. Of these oscillating transients, some resulted in a steady state, some in complete blockage, and others oscillated indefinitely, never achieving either condition. Ice bands have been shown to cause oscillations in other studies, but Gilpin [5] did not establish the existence of that structure for the range of parameters considered here. The mechanism causing the oscillations in this study has not been positively identified, but the following is speculated. It was inferred from thermocouple readings that a portion of the tube near the inlet was bare during smooth transients which ended in a steady state, as a result of moderate cooling. As the coolant temperature was lowered, this same portion alternated between being bare and being ice covered as the transients became oscillatory. When the coolant temperature was lowered severely, the entire tube was ice covered and the transients proceeded smoothly to blockage. This is no doubt related to the fluctuations of flow rate and pressure drop found in this study.

In some of the previous studies, the tube-wall temperature was assumed to be uniform, and was used in defining a dimensionless temperature. This assumption of uniform tube-wall temperature was observed to be reasonable for transients ending in steady state, those transients developing a thin frozen region. However, for those cases which terminated with complete blockage or those which oscillated indefinitely (both cases apparently having thicker ice layers), this assumption is invalid. During a blockage transient, the wall temperature was not at all uniform, with axial variations of as much as 5.4°C existing. Nor was the wall temperature constant in time during these transients, often decreasing by as much as 2.0°C. In the case where flow rate and pressure drop oscillated continuously, the wall temperatures also oscillated such that any one thermocouple often indicated a value differing from the mean of the other four by as much

NOMENCLATURE

a_l thermal diffusivity of test liquid
D inside diameter of developing and freezing sections
Fo Fourier number, $(a_l \times \text{time})/(D(D/4))$
H static pressure difference across the entire system
k_l thermal conductivity of the liquid phase
k_s thermal conductivity of the solid phase
L length of the freezing section
nu kinematic viscosity of test liquid or coolant, as appropriate
P static pressure drop
P_e static pressure at test-section exit
P_i static pressure at developing-section inlet
P_o static pressure at test-section inlet
Pr Prandtl number, nu/a_l
P^* non-dimensional test-section static pressure drop, $(P_o - P_e)2/(roV^2)$
R inlet-section : test-section pressure drop ratio (no ice), $(P_i - P_o)/(P_o - P_e)$
Re Reynolds number, $(VD)/nu$, based on tube diameter or shell i.d. – tube o.d.
ro density of test liquid
T_c bulk temperature of coolant at test-section inlet
T_f freezing temperature of test liquid
T_o bulk temperature of test liquid at test-section inlet
T^* non-dimensional temperature, $k_s/k_l(T_f - T_c)/(T_o - T_f)$
V mean inlet velocity
Z^* $[(Re\ Pr)_{\text{test liquid}}/(Re\ Pr)_{\text{coolant}}][D/4L]$.

Table 1. Experimental data and computed results

Orifice	H (cm)	Re	T_o (°C)	T_c (°C)	T^*	$Z^* \times 10^4$	Response
None	7.9	4560	4.9	−6.4	4.8	5.4	BL, OSS
None	7.9	4540	4.8	−7.0	5.4	5.4	BL, SMO
None	7.9	4520	4.8	−5.9	4.5	5.4	BL, OSS
None	7.9	4520	4.8	−5.4	4.2	5.4	SS, OSS
None	7.9	4540	4.8	−5.0	3.9	5.4	SS, SMO
None	7.9	4540	4.8	−6.7	5.2	5.4	BL, SMO
No. 1	13.8	4530	4.8	−5.6	4.3	5.4	SS, OSS
No. 1	13.8	4530	4.8	−6.0	4.6	5.4	SS, OSS
No. 1	13.8	4530	4.8	−8.4	6.5	5.4	BL, SMO
No. 1	13.8	4530	4.8	−6.1	4.7	5.4	CON OSS
No. 1	13.8	4530	4.8	−6.7	5.2	5.4	BL, OSS
No. 1	13.8	4530	4.8	−7.1	5.5	5.4	BL, SMO
No. 1	22.7	5900	4.7	−6.1	4.8	7.0	SS, SMO
No. 1	22.7	5900	4.7	−8.8	6.9	7.0	BL, OSS
No. 1	22.7	5890	4.7	−8.2	6.5	7.0	CON OSS
No. 1	22.7	5900	4.7	−9.2	7.2	7.0	BL, OSS
No. 1	22.7	5900	4.7	−8.2	6.5	7.0	SS, OSS
No. 1	22.7	5880	4.7	−8.3	6.5	7.0	BL, OSS
No. 1	22.7	5890	4.7	−7.7	6.1	7.0	SS, OSS
No. 1	22.7	5900	4.7	−9.7	7.6	7.0	BL, OSS
No. 1	35.6	7590	4.7	−10.2	8.0	9.0	SS, SMO
No. 1	35.6	7590	4.7	−11.2	8.8	8.5	BL, OSS
No. 1	35.6	7550	4.7	−6.1	4.8	8.9	SS, SMO
No. 1	35.6	7560	4.7	−8.1	6.4	8.9	SS, SMO
No. 1	35.6	7540	4.7	−12.2	9.6	8.5	BL, OSS
No. 1	35.6	7550	4.6	−11.2	9.0	8.5	BL, OSS
No. 1	35.6	7550	4.7	−11.1	8.7	8.5	BL, OSS
No. 1	35.6	7550	4.7	−11.2	8.8	8.5	BL, OSS
No. 1	35.6	7550	4.7	−11.1	8.7	8.5	SS, OSS
No. 1	35.6	7590	4.7	−10.8	8.5	8.5	SS, OSS
No. 1	35.6	7590	4.7	−11.1	8.7	8.5	SS, OSS
No. 1	35.6	7550	4.7	−12.8	10.1	8.5	BL, OSS
No. 1	35.6	7550	4.7	−14.1	11.1	8.0	BL, SMO
No. 1	48.3	9000	4.7	−8.1	6.4	10.7	SS, SMO
No. 1	48.3	9000	4.7	−6.2	4.8	10.7	SS, OSS
No. 1	48.3	8990	4.7	−14.2	11.2	9.6	BL, OSS
No. 1	48.3	8990	4.7	−13.5	10.6	9.6	SS, OSS
No. 1	48.3	8900	4.7	−15.0	11.8	9.6	BL, OSS
No. 1	48.3	9000	4.7	−16.1	12.7	9.6	BL, SMO
No. 1	48.3	9040	4.9	−14.6	11.0	9.6	BL, OSS
No. 1	48.3	9000	4.7	−14.1	11.1	9.6	SS, OSS
No. 1	48.3	9000	4.7	−10.1	8.0	10.7	SS, SMO
No. 1	48.3	9000	4.7	−12.3	9.7	10.1	SS, OSS
No. 1	60.5	10 160	4.7	−14.9	11.7	10.8	SS, OSS
No. 1	60.5	10 160	4.7	−14.2	11.2	10.8	SS, OSS
No. 1	60.5	10 140	4.7	−15.8	12.4	10.8	CON OSS
No. 1	60.5	10 140	4.7	−16.3	12.8	10.8	SS, OSS

(continued)

Table 1. (*continued*)

Orifice	H (cm)	Re	T_o (°C)	T_c (°C)	T^*	$Z^* \times 10^4$	Response
No. 1	60.5	10 140	4.7	−16.9	13.3	10.8	BL, OSS
No. 1	60.5	10 140	4.7	−18.4	14.5	10.8	BL, SMO
No. 2	41.9	4470	4.8	−6.2	4.8	5.3	SS, SMO
No. 2	41.9	4470	4.8	−7.0	5.4	5.3	SS, OSS
No. 2	41.9	4500	4.9	−6.8	5.1	5.3	SS, OSS
No. 2	41.9	4500	4.9	−7.1	5.4	5.3	SS, OSS
No. 2	41.9	4470	4.8	−7.4	5.7	5.3	SS, OSS
No. 2	41.9	4490	4.9	−6.6	5.0	5.3	SS, OSS
No. 2	41.9	4470	4.9	−9.6	7.2	5.3	BL, SMO
No. 2	41.9	4470	4.9	−7.9	6.0	5.3	SS, OSS
No. 2	41.9	4490	4.8	−8.5	6.6	5.3	BL, OSS

Note: SS = steady state; BL = complete blockage; SMO = smooth; OSS = oscillatory; CON OSS = continuously oscillating.

as 2.5°C. So as to provide a consistent and unambiguous comparison between the steady-state, blockage, and continuously oscillating cases, the inlet coolant temperature (which was held constant during each transient) was chosen instead of wall temperature in defining a dimensionless temperature, T^*. This parameter gives an indication of the degree of cooling applied; though now the imposed condition is convective rather than being one of prescribed temperature. The use of coolant inlet temperature instead of wall temperature in defining T^* is consistent with the approach taken by Gilpin [5].

A second dimensionless variable, Z^*, involving the pipe L/D and the Reynolds and Prandtl numbers of both fluids was also defined. This parameter, while similar to that used in the literature discussing the case of constant wall temperature, has been modified to account for the convective boundary condition.

A portion of the data is represented in Fig. 1. These data cover a tube-side Reynolds number range from approximately 4500 to slightly over 10 000 and were run with upstream resistance No. 1 (orifice No. 1 in the developing section). Each point on this plot of Z^* vs T^* indicates the final state of a given transient. These data show the dividing line between conditions leading to blockage and those leading to a steady state to be approximately linear, with some scatter across the line. As might be expected, this dashed line approximates the locus of points representing continuously oscillating transients. The region lying between the two solid lines contains combinations of Z^* and T^* which yielded transients of the oscillatory type, those above the dashed line ending in steady states and those below terminating with blockage. Variations in Z^* were achieved by varying the initial Reynolds number of the water, and T^* was varied by changing the coolant inlet temperature. This figure indicates that a decrease in Z^* (associated with a decrease in initial Reynolds number of the water or an increase in the coolant Reynolds number) promotes blockage for a given value of T^*. Also seen is that increases in T^* (associated with decreases in coolant inlet temperature) at a given value of Z^* promote blockage. This same effect results from an increase in tube L/D or coolant Reynolds number.

A somewhat different way of presenting blockage data is shown in Fig. 2. Steady-state test-section pressure drop is plotted vs initial Reynolds number for selected values of T^* along with the system flow characteristic curve for the case with no external cooling or no ice in the tube. As initial Reynolds number decreased, the final test-section pressure drop decreased until the system approached complete blockage. At conditions near those which caused this blockage, a decrease in initial Reynolds number caused a sharp increase in final test-section pressure drop, as shown by the dashed lines in the figure. When complete blockage of the test-section occurred, the pressure drop across this section became equal to the static pressure drop across the entire system, these points being indicated on Fig. 2 at the intersection of the dashed lines representing the test section and the solid line representing the total system pressure drop. One may see that the initial Reynolds numbers at which blockage occurred

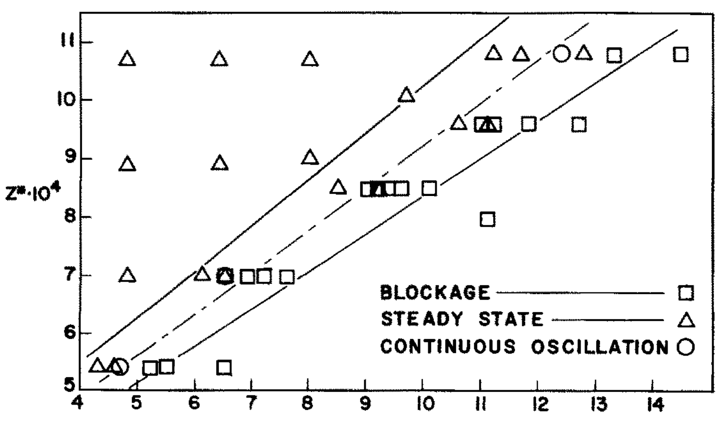

FIG. 1. Effects of coolant inlet temperature (T^*) and initial Reynolds number (Z^*) on freezing-section response.

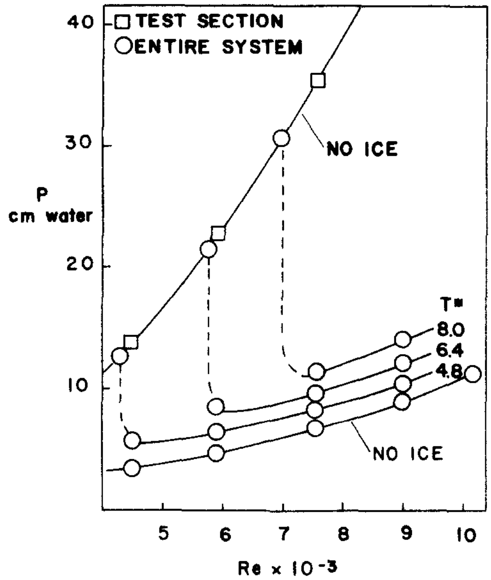

FIG. 2. System and freezing-section pressure drop as determined by coolant inlet temperature (T^*) and initial Reynolds number.

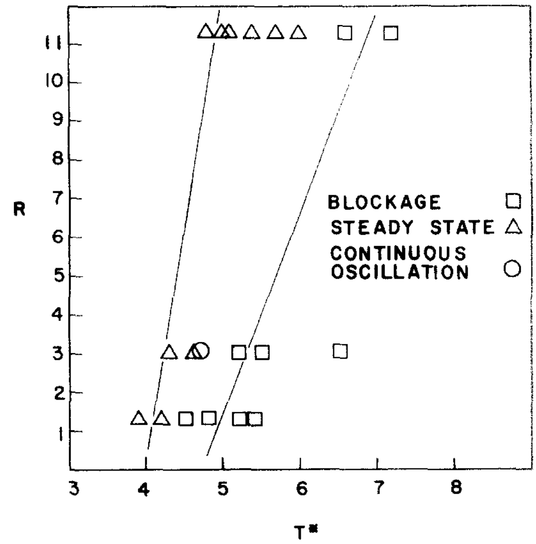

FIG. 4. Freezing-section response as a function of inlet coolant temperature (T^*) for three upstream resistances and an initial Reynolds number of approximately 4500.

for given values of T^* correspond to blockage conditions in Fig. 1.

Orifice-type flow restrictions were placed in the inlet of the developing section to alter the flow characteristics, and it was observed (Fig. 3) that this had a significant effect on the freezing characteristics of the test section for a given Reynolds number. Figure 4 presents data for the three upstream flow characteristics, with all cases being run at a Reynolds number of approximately 4500. The flow resistance of the developing section with no orifice corresponded to an inlet-section pressure drop of 4.4 cm of water at a Reynolds number of 4500. The two orifices were associated with inlet-section resistances 1 and 2 and caused pressure drops across this section of 10.4 and 38.5 cm of water, respectively. The pressure drop across the freezing section at this Reynolds number was 3.4 cm of water. The solid lines again enclose that region in which the transient responses were noticeably oscillatory. The parameter R represents the ratio of the upstream flow resistance to that of the test section with no ice. It is seen that decreases in R for a given value of T^* tend to drive the system toward blockage. This is reasonable if one considers that a lower value of R implies that a lower upstream head is required to generate a given initial Reynolds number, and therefore the head ultimately available to drive the flow as the tube blocks (these being one and the same head) is less. With a reduced available head, blockage occurs more readily. It is also apparent from Fig. 4 that the range of parameters causing oscillations increases as the ratio of upstream resistance to that of the test section increases.

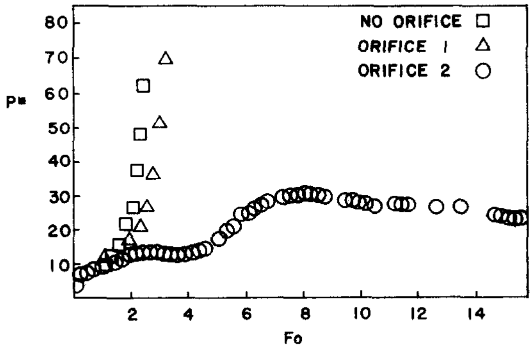

FIG. 3. Freezing-section response for three values of upstream resistance, with an initial Reynolds number of 4500 and a T^* of approximately 5.5.

CONCLUSIONS

As pointed out by Gilpin [5], freeze blockage is a system problem which requires consideration of the characteristics of the flow source. Therefore, the quantitative results presented here are not general, but are specific to this system. The character of the responses would, however, be similar in other systems of this type, and these general conclusions may be drawn on the basis of this study.

(1) Certain combination of initial Reynolds number and dimensionless temperature cause oscillations in flow rate and pressure drop during the freezing of a turbulent internal flow. These transients may terminate in a steady state, in a condition of complete blockage, or may continue to oscillate indefinitely. The oscillations disappear if conditions are altered, and the transients then proceed smoothly.

(2) Increases in the initial Reynolds number tend to prevent complete blockage for a given value of T^*. It was also found that as the initial Reynolds number is increased, the range of values of the dimensionless temperature, T^*, that causes oscillatory behavior increases.

(3) The nature of the transient freezing response was shown to be strongly dependent on the relationship of the upstream flow resistance to that of the freezing section, with decreases in this ratio tending to promote blockage for a given value of T^*. Increases in this ratio of upstream to freezing-section flow resistance also cause an increase in the range of T^* values associated with oscillatory behavior for a given initial Reynolds number.

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The transient solidification of weldpools

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INTRODUCTION

In a recent paper (1984) we developed a formulation and presented computed results describing the transient development of weldpools in spot welds, produced by the TIG (tungsten inert gas) welding process. The physical picture invoked a solid metal block onto which a plasma jet was made to impinge. This plasma jet provided a spatially distributed heat source, causing partial melting of the block. At the same time the molten pool (termed weldpool) would undergo recirculating motion as driven by the combination of:

(a) buoyancy forces;
(b) electromagnetic forces and;
(c) if applicable surface tension forces, due to temperature gradients at the free surface.

In the formulation presented appropriate scaling factors were introduced for time and length, so that the numerical computer results could be usefully generalized.

It was shown that under certain conditions (when the modified Peclet number was large) convection appreciably affected the heat transfer process and hence the shape of the weldpool. While under other conditions (small values of the modified Peclet number) conduction was the dominant mechanism for heat transfer in the weldpool.

In a physical sense the former case corresponded to surface tension driven flows and/or electromagnetically driven flows, caused by a strongly divergent current path in the weldpool, resulting in weldpool shapes that markedly deviated from the idealized shape that one would obtain from the classical point source solutions.

In contrast in the absence of significant convection effects, i.e. for broadly distributed heat sources, the weldpools were essentially ellipsoidal in shape.

The treatment developed in the earlier paper has answered one part of the real physical problem, namely what are the factors that govern the transient growth and shape of a weldpool. However, an equally important part of the weldpool problem has yet to be answered, namely how does convection affect the solidification of the molten region.

In a physical sense this problem may be stated as follows. Due to the action of the plasma jet and the attendant buoyancy, surface tension and electromagnetically driven flows, a weldpool is generated and is undergoing recirculatory motion. Then the supply of current and hence of thermal energy is discontinued, thus the direction of the melt–solid boundary advancement is reversed and the weldpool is then allowed to solidify.

The question is then to describe this solidification process and also to represent the transient, progressively shrinking weldpool, since the structure of the solidified material, of considerable interest in the assessment of the weldment quality, may be markedly affected by the motion of the liquid, with which it is in contact during the solidification process.

Let us consider a weldpool, which is axisymmetric in shape, such as sketched in Fig. 1. The growth of this weldpool has been initiated at time $-t_0$ and as a result there developed temperature profiles both within the weldpool and in the base metal and a corresponding circulation pattern has also

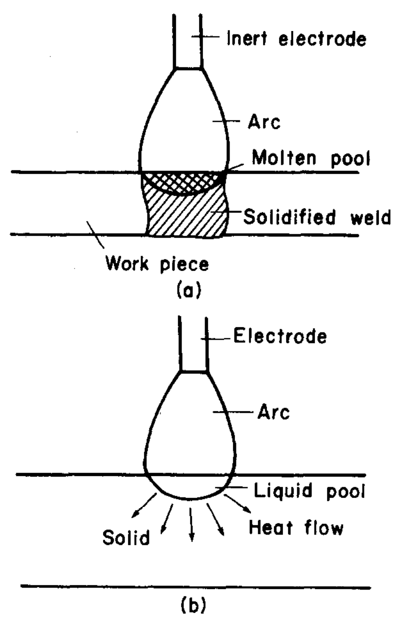

Fig. 1. Schematic sketch of a TIG welding system.