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SOLIDIFICATION OF FLOWING LIQUID IN AN ASYMMETRIC COOLED PARALLEL-PLATE CHANNEL

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ABSTRACT

An experimental study has been performed to investigate the ice-formation phenomena of water flow between two horizontal parallel plates, with the lower wall kept at a temperature below the freezing temperature of the liquid. A detailed and comprehensive investigation of the morphology of the ice-structure is given. It is shown, that the different shapes of ice-layers can be classified with the help of a θ_c - Re_D diagram.

Introduction

Ice-formation phenomena can be observed in many processes, such as the freezing of water in pipes, the blockage of chemical process lines, and the freezing of liquid metals in heat exchangers. Many theoretical and experimental studies have been performed for fluid flow with solidification in circular tubes and parallel-plate channels and its effect upon the laminar-flow heat transfer [1], [2], [3], [4]. On the other hand, there are only few theoretical studies which deal with the prediction of ice-layers for turbulent flow [5], [6]. In the theoretical treatment of solidification in turbulent flow it was generally assumed, that the shape of the ice is smooth and monotonically growing in thickness with an increasing distance from the entrance of the chilled region. However, if the ice-layer is not thin enough, there will be an interaction between the turbulent flow, the shape of the ice and the heat transfer at the ice-water interface. Under certain conditions these interactions result in an instability of the ice-layer. The possibility, that the ice-layer might be unstable against finite perturbations for a range of cooling parameters was first recognized by Gilpin [7], [8]. He observed that wavy ice-layers developed in a cooled pipe without perturbing the frozen crust. On the other hand, the ice-layer on a flat plate had to be perturbed by melting a heated copper pipe half a diameter into the ice. Without doing this, only one wave could be observed in the ice-layer on a flat plate [9], [10]. Seki et al. [11] performed experiments in a parallel-plate channel with both walls kept at a temperature below the freezing temperature of the water. He investigated only a relatively small range of flow-rate Reynolds numbers and cooling parameters θ_c. Therefore, he was able to observe only one wave in the ice. More recently Weigand and Beer [12] presented a detailed experimental investigation of the morphology of ice-structure in a parallel-plate channel with both walls kept at a temperature below the freezing temperature of the water. In [12] it could be observed, that ice-layers with many waves developed without perturbing the frozen crust. This development of ice-bands was found to be quite similar to the development of wavy ice-layers in a cooled pipe. Only one experimental investigation is known which deals with the asymmetric freezing of a fluid in a cooled parallel-plate channel, where the lower wall was kept at a temperature below the freezing temperature of the water [13]. The major concern in [13] was the measurement of the velocity profiles and the turbulence intensity in the flow along the developing ice-layer surface only at flow-rate Reynolds numbers Re_D of approximately 12000. The authors observed a wavy ice-layer with two waves in the test section. No attempt was made in [13] to classify the different ice-structures with the help of a θ_c - Re_D diagram.

The subject of the present paper is the presentation of a detailed and comprehensive experimental investigation of the morphology of ice-structure in a parallel-plate channel, where the lower wall is kept at a temperature below the freezing temperature of the water. This study intends to clarify some of the mechanisms which lead to an instability of the ice-layer in a cooled parallel-plate channel, subjected to symmetric and asymmetric cooling.

Experiment

Experimental Apparatus

A schematic outline of the experimental apparatus is shown in Fig. 1. The apparatus mainly consists of a test section, a refrigeration unit and two circulation systems for water and coolant, respectively. Water is delivered from a tank by a centrifugal pump. The water flow-rate can be measured with the help of a Venturi-nozzle. In order to achieve a fully developed turbulent velocity profile at the entrance of the test section, an insulated calming section, 3 m in length, was installed in front of the test section. The water temperature was measured with three thermocouples at the inlet (T_0) as well as at the exit (T_E) of the test section. Subsequently the water passed a calming section and was fed back into the water tank. The water temperature was controlled by a NTC controlled heater, as shown in Fig. 1. The test section consists of the lower 30 mm thick, cooled copper plate and an insulated upper plate. The lower copper plate was devided into nine independent chambers, through which the temperature controlled coolant was circulated independently with high velocity. To achieve a uniform temperature in each chamber of the copper plate, channels were milled into the interior to facilitate the circulation of the coolant. For the observation and measurement of the ice-layer thickness, the front and the back side of the test section were covered by transparent polycarbonat plates, 12 mm in thickness, allowing for photographic registration of the ice-layer. The rectangular channel, formed by the lower cooled wall, the upper insulated wall and the polycarbonat plates, has a width of 100 mm. The clearance between the upper and the lower wall is 24 mm. The surface temperatures of the upper wall and the lower cooled wall

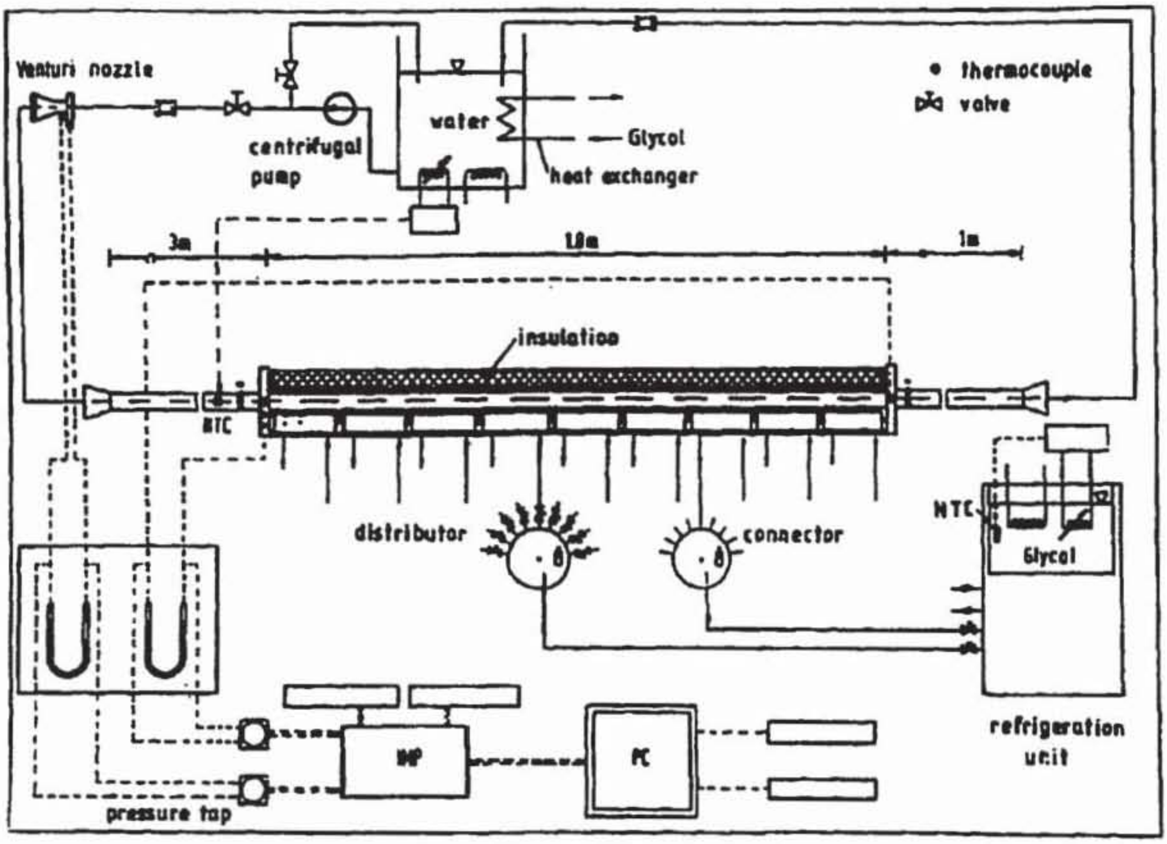

FIG. 1
Schematic Drawing of Experimental Apparatus

were measured by 20 calibrated chromel-alumel thermocouples, inserted into holes, drilled from the backside of the plates. The thermocouple junctions were positioned at the centerline of the plates. The main parts of the coolant flow loop consist of a refrigeration unit, a coolant distributer connected with nine adjustable valves, a coolant collector and thermometric measuring instruments. The temperature of the coolant was controlled by a NTC controlled heater, installed in the coolant tank. Therefore, the temperature of the coolant differed by not more than 0.1 K from the desired value during an experimental run.

Operating Procedures

Starting the experiments, the flow-rate of the water, inlet and outlet temperature of the water, the temperature of the coolant, the temperature of the cooled copper plate as well as the static pressure difference across the test section were controlled. All data were recorded after steady state conditions had developed. The thickness of the ice-layer was measured by two independent methods:

- Photographs were taken at different times and evaluated afterwards.
- The ice-layer thickness was measured with the help of a microscope, fastened sliding in front of the channel, with three selectable enlargements.

As a consequence, the ice-layer thickness could be measured with good accuracy of the order less than

0.1 mm. The range of conditions employed in the present investigation were:

Reynolds number Re_D:	9000	$\leq$	Re_D	$\leq$	50000
Inlet temperature T_0:	273 K	$\leq$	T_0	$\leq$	281 K
Wall temperature T_w:	257 K	$\leq$	T_w	$\leq$	270 K

The wall temperature T_w was defined as an arithmetic mean value of all temperatures measured at the lower cooled copper plate. Because the cooled copper plate was subdivided into nine independent chambers, the wall temperatures seldom differed by more than 0.5 K along the length. The standard deviation of T_w was found to be smaller than 0.25 K. The cooling temperature ratio $\theta_c=(T_F-T_w)/(T_0-T_F)$ varied in the range $0 \leq \theta_c \leq 20$.

Results and Discussion

Classification of ice-structures

All the different shapes of steady state ice-layers can be classified according to Fig. 2, which is a θ_c - Re_D diagram.

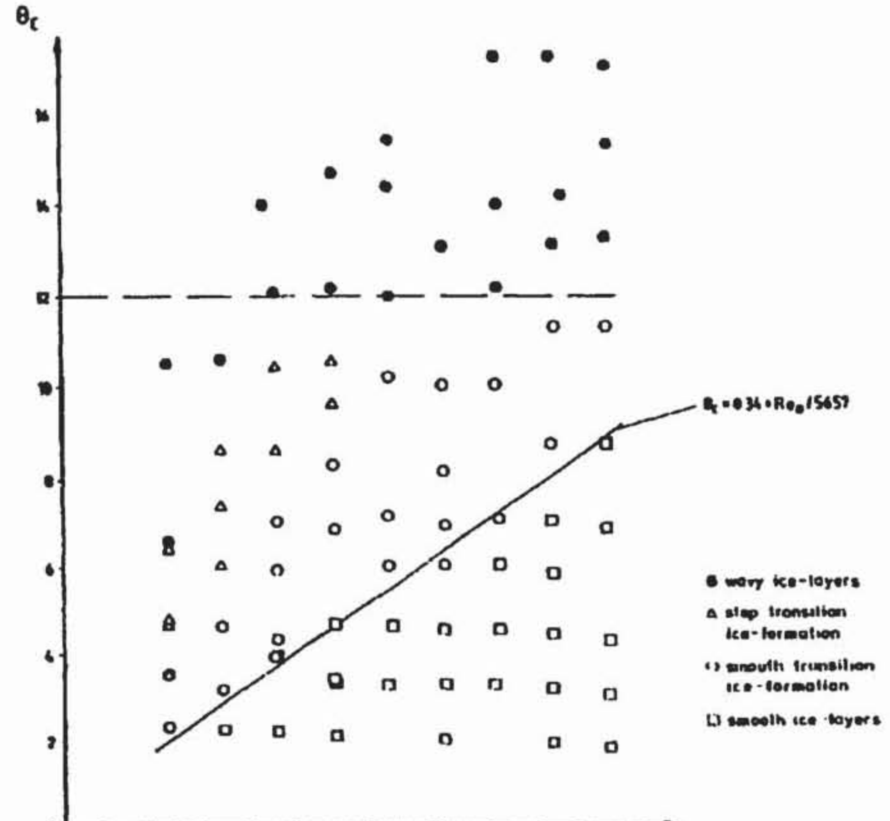

FIG. 2
Summary of different Freezing Phenomena on θ_c - Re_D Coordinate System

The following types of ice formation regimes were found in experiments:

Smooth ice-layers

For low values of the cooling parameter θ_c

$$\theta_c < 0.34 + \frac{Re_D}{5657} \tag{1}$$

a smooth ice-layer can be observed. For this type of ice-formation, the ice-layer thickness increases sharply in the entrance region of the cooling section and growths slowly and monotonically for larger values of the axial coordinate.

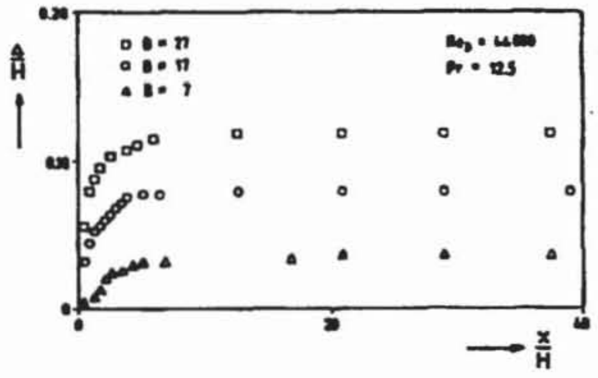

FIG. 3
Ice-layer Thickness for various cooling Parameter B

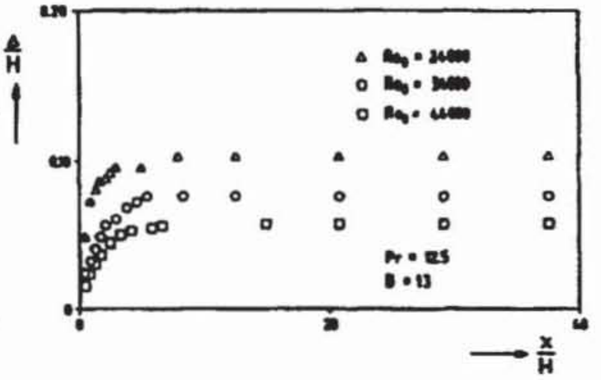

FIG. 4
Ice-layer Thickness for various Re_D

Fig. 3 and Fig. 4 show measured ice-layers, plotted as a function of the axial coordinate. Fig. 3 elucidates that an increasing cooling parameter $B = k_s/k_L\ \theta_c$ results in a thicker ice-layer for a fixed value of the Reynolds number and a given Prandtl number. Fig. 4 shows the effect of a variation in the Reynolds number for $B = 13$ and $Pr = 12.5$. It is obvious, that an increasing Reynolds number results in a decreasing ice-layer thickness. This is due to the intensified heat transfer from the fluid to the ice-layer with growing Reynolds numbers. It should be recognized that smooth ice-layers are generally relatively thin. For example, the maximum thickness of the ice-layer for $Re_D = 24000$ in Fig. 4 is only 2.4 mm.

Transition ice-formation

If the cooling ratio θ_c is increased, so that the inequality according to eq. (1) is violated, a wave is formed near the entrance of the test section. In literature it is entitled "transition" ice-layer. Fig. 5 shows the effect of a variation in Reynolds number for a given value of the cooling parameter $B = 27$, and $Pr = 13$. It can be observed that an increasing Reynolds number results in a decreasing ice-layer thickness. Also, it can be seen that for the highest Reynolds number $Re_D = 34000$ only a very small wave is formed near the entrance. This type of ice-formation is known in literature as a "smooth transition" ice-formation, because the flow passage expands gradually in flow direction after a contraction near the entrance. For decreasing values of the Reynolds number, the cross sectional area increases very sharply after the ice-layer had reached the maximum thickness. The sharp expansion in flow direction results in

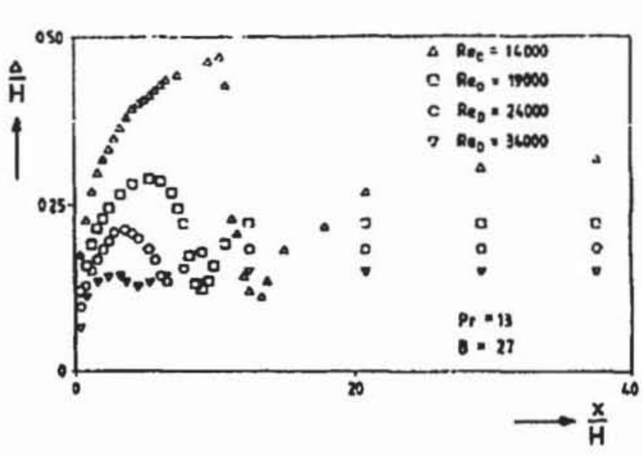

FIG. 5
Transition Ice-layers for various Values of Re_D

a flow separation in this region. This type of ice-formation is known as "step transition" ice formation. The occurence of one wave near the entrance of the test section can be explained according to Weigand and Beer [12]. They stated, that the flow will be laminarized in the entrance section of the chilled region because of strong acceleration of the flow caused by the strongly increasing ice-layer thickness. For larger values of the axial coordinate the increase in ice-layer thickness tends to zero (Fig. 3) and, therefore, the heat transfer at the solid liquid interface increases, which results in a decreasing ice-layer thickness. On the other hand, Hirata et al. [10] explained the occurence of one wave in the ice-layer on a flat plate quite different. They pointed out, that a laminar boundary layer will be formed at the leading edge of the plate. After a distance from the beginning of the plate, this laminar boundary layer will be unstable and changes into a turbulent boundary layer. Because of this fact, the heat transfer at the ice-liquid interface increases and a wave is formed in the ice-layer on the cooled plate.

The following Fig. 6 and Fig. 7 show a variation of the cooling parameter B for fixed values of Re_D and Pr. In both plots, it can be observed, that an increasing cooling parameter B results in a thicker ice-

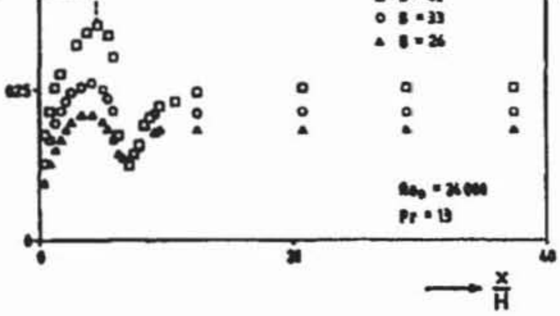

FIG. 6
Ice-layer Thickness for $Re_D = 24000$ and various B

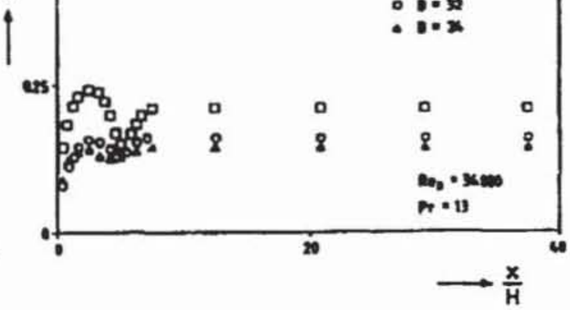

FIG. 7
Ice-layer Thickness for $Re_D = 34000$ and various B

layer for a specified value of the Prandtl number and a given value of the flow-rate Reynolds number. An other suprising detail is the fact that the distance x_{tr}/H between the entrance of the chilled region and the point for which the ice-layer reaches its maximum thickness, is only a function of the Reynolds number. This is elucidated by Fig. 6 and Fig. 7. A further interesting detail is that the minimum thickness of the ice-layers also seems to depend only on the Reynolds number and not on the cooling parameter B. The axial distance x_{tr}/H can be expressed as a function of the Reynolds number by the relation

$$\frac{x_{tr}}{H} = 2.33 \cdot 10^5 \, (Re_D)^{-1.87} \tag{2}$$

As can be seen from Fig. 8, eq. (2) correlates reasonably well the present experimental results within a limit of about ± 25 percent.

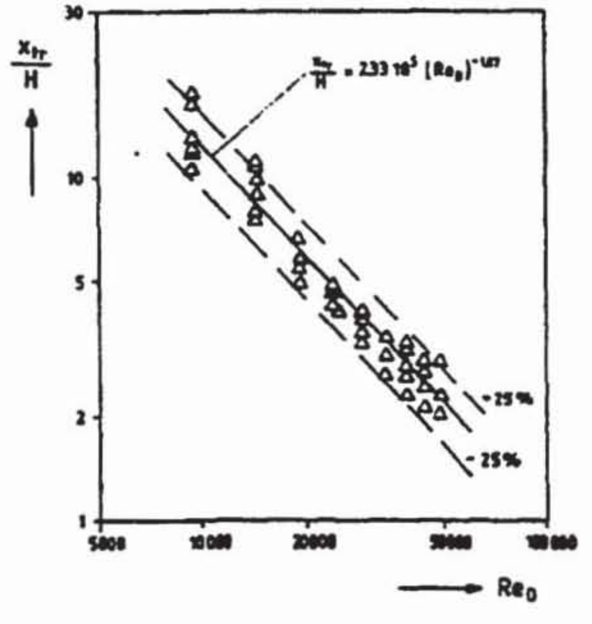

FIG. 8
Transition Point x_{tr}/H as a Function of the Reynolds number

Wavy ice-layers

Increasing the cooling ratio θ_c for a given value of the Reynolds number, leads to an unstable ice-layer and a wavy ice structure can be observed.

It is interesting to notice, that wavy ice-layers developed in the present study without perturbing the frozen crust. This was also stated by Tago [13]. On the other hand, wavy ice-layers on a flat plate developed only by perturbing the frozen crust by melting a heated copper pipe half a diameter into the ice [9]. This suggests that the reason for the instability of the solid crust might be the preceeding laminarization of the flow, which is now more susceptible to perturbations. In Fig. 10 a wavy ice-layer

FIG. 9
Wavy Ice-layer for $Re_D = 34000$, $Pr = 13$, $\theta_c = 13$

FIG. 10
Wavy Ice-layer for $Re_D = 44000$, $Pr = 13$, $\theta_c = 17.3$

is shown for a larger value of the cooling ratio θ_c. It can be seen, that the wave length decreases with growing values of the cooling ratio θ_c. In experiment it could be observed that high values of the cooling ratio θ_c lead to three dimensional effects in the formation of the ice-layer. For such high values of the cooling ratio θ_c it can be assumed that no steady state conditions can be reached. The shape of the ice-layer was found to change very slowly with time.

Differences between asymmetric and symmetric ice-layer formation in a cooled parallel-plate channel

Finally it has to be pointed out, that the θ_c - Re_D diagram (Fig. 2) for asymmetric freezing in a parallel-plate channel looks quite different than that for symmetric freezing in a parallel-plate channel, where both walls are kept at the same temperature below the freezing temperature of the flowing liquid [12]. Fig. 11 shows the θ_c - Re_D diagram for symmetric freezing in a parallel-plate channel, according to [12]. In the case of symmetric freezing in a parallel-plate channel, smooth ice-layers occur for

$$\theta_c < -0.41 + \frac{Re_D}{7077} \quad , \qquad (Re_D > 6000) \tag{3}$$

This shows that for a fixed value of the flow-rate Reynolds number Re_D, smooth ice-layers in a parallel-plate channel with only one cooled wall, will be in existence for higher values of θ_c than for the symmetric case (eq. (3)). This fact can be easily understood by recognizing that the acceleration of the flow in the case of symmetric freezing in a parallel-plate channel is more pronounced than in the case of asymmetric freezing. This means that laminarization of the flow occurs for lower values of the cooling ratio θ_c in the symmetric case. Further it is interesting to note, that step transition ice formation through out the whole range of flow-rate Reynolds numbers could only be observed in a parallel-plate channel

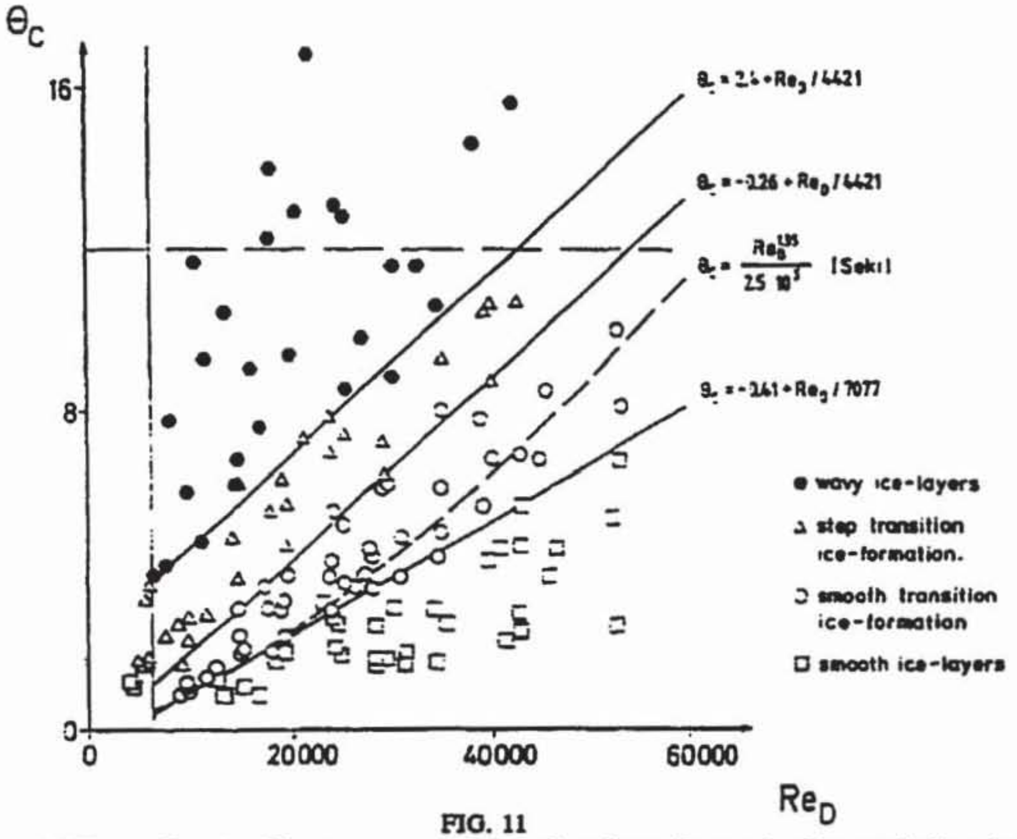

FIG. 11
Summary of different Freezing Phenomena on θ_c - Re_D Coordinate System for Symmetric Freezing in a Parallel-Plate Channel

with symmetric cooling (Fig. 11). In the present case of asymmetric freezing (Fig. 2), step transition ice formation was restricted to Reynolds numbers $Re_D \leq 24000$. For higher values of Re_D, the appearance of flow separation in the expansion region of the first wave was related to the appearance of a wavy ice-layer. Gilpin et al. [9] found out that the ice-layer on a flat plate was unstable against finite perturbations for cooling ratios $\theta_c < 12$. This result is well confirmed in the case of asymmetric freezing (Fig. 2). Only for low values of the Reynolds number ($Re_D \approx 9000$) wavy ice-layers developed for $\theta_c < 12$. This is due to very thick ice-layers, causing a strong acceleration of the flow in the entrance region. The situation is quite different in case of symmetric cooling. Here, the appearance of wavy ice-layers strongly depends on the flow-rate Reynolds number. According to [12] it can be assumed that wavy ice-layers develop for

$$\theta_c > 2.4 + \frac{Re_D}{4421} \quad , \quad (Re_D > 6000) \tag{4}$$

However, for higher values of the Reynolds number it must be supposed that the boundary, described by eq. (4), is no longer a straight line. By taking the experimental results of the asymmetric freezing process into account, it can be assumed, that eq. (4) will approach the boundary $\theta_c = 12$ (dotted line in Fig. 2 and Fig. 11) for higher values of the Reynolds number. Unfortunately not enough experiments are available to confirm this hypothesis.

Conclusions

According to the experimental results of the present investigation concerning the asymmetric freezing of water flow between horizontal parallel plates, where only the lower plate is cooled, the following major conclusions may be drawn:

1. It was found out that the occurence of wavy ice-layers in an asymmetric cooled channel is nearly independent of the flow-rate Reynolds number. This fact is quite different to the development of wavy ice-layers in a symmetric cooled channel.
2. Wavy ice-layers developed in an asymmetric cooled channel without perturbing the frozen crust, which is different from the development of ice-bands on a cooled flat plate.
3. It can be assumed, that the occurence of wavy ice-layers is strongly related to the appearance of flow separation in the expansion region of the flow passage behind the first wave.
4. Flow laminarization plays an important role in the instability phenomena of ice-layers in a parallel-plate channel.

Acknowledgement

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Nomenclature

$B = k_s/k_L\ \theta_c$	dimensionless freezing parameter
$D = 2\,H$	hydraulic diameter
H	distance between parallel plates
k_s	thermal conductivity of the ice
k_L	thermal conductivity of the liquid
Pr	Prandtl number
$Re_D = \bar{u}_0\, D/\nu$	Reynolds number based on D
T_F	freezing temperature of the liquid
T_w	wall temperature
T_0	constant inlet temperature of the liquid
T_E	outlet temperature of the liquid
$\bar{u}_0$	mean axial velocity at the entrance of the test section
x	axial coordinate
x_{tr}	transition point
Δ	ice-layer thickness
$\theta_c = (T_F-T_w)/(T_0-T_F)$	dimensionless temperature difference
ν	kinematic viscosity

References

1. R.D. Zerkle and J.E. Sunderland, J. Heat Transfer 90, 183 (1968).
2. D.G. Lee and R.D. Zerkle, J. Heat Transfer 91, 583 (1969).
3. Y. Kikuchi, Y. Shigemasa and T. Ogata, J. Nucl. Sci. Technol. 23, 43 (1986).
4. B. Weigand and H. Beer, Z. Wärme- und Stoffübertragung 26, 233 (1991).
5. A. Shibani and M. Özisik, J. Heat Transfer 99, 20 (1977).
6. B. Weigand and H. Beer, Z. Wärme- und Stoffübertragung (accepted for publication).
7. R.R. Gilpin, J. Heat Transfer 103, 363 (1981).
8. R.R. Gilpin, Heat Transfer - San Diego 1979, AICHE Symp. series 189, 75 , 89 (1979).
9. R.R. Gilpin, T. Hirata and K.C. Cheng, J. Fluid Mech. 99, 619 (1980).
10. T. Hirata, R.R. Gilpin and K.C. Cheng, Int. J. Heat Mass Transfer 22, 1435 (1979).
11. N. Seki, S. Fukusako and G.W. Younan, J. Heat Transfer 106, 498 (1984).
12. B. Weigand and H. Beer, Proceedings of the Third Int. Symp. on Cold Regions Heat Transfer, Alaska, 167 (1991).
13. M. Tago, S. Fukusako, M. Yamada, A. Horibe and O. Okagaki, Proceedings of the Third Int. Symp. on Cold Regions Heat Transfer, Alaska, 257 (1991).