AN EXPERIMENTAL STUDY OF WATER FREEZING IN CYLINDRICAL STAGNATION FLOW

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Abstract- In this experimental study, we investigate the freezing of water in cylindrical stagnation flow to compare the degree of agreement of the results with the theory solution. We are also looking for a way to determine the flow regime. The water impinges vertically on a cold flat plate while the water outlet section is cylindrical. The water starts to freeze when the substrate plate is sufficiently cold. The effects of distance between the outlet and the substrate plate, magnitude of the flow strain, water temperature, and the plate involved in ice formation, and most importantly, the final thickness of the ice have been investigated. Results are compared for validation with those of a numerical solution. The results show a good agreement in the middle of the ice thickness curve. As a result, the speed of ice formation is very high at first, and declines sharply with a steep slope. More importantly, a particular definition is employed for achieving the regimes (laminar, turbulent, or transitional) in stagnation flow. According to the results, the ice thickness in laminar flow is more than in turbulent one.

Keywords: Experimental investigation, Water solidification, Stagnation flow, Cylindrical freezing, Ice thickness

NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| c      | Heat capacity coefficient (\(\frac{KJ}{kg.K}\)) |
| D      | Distance (mm) |
| h      | Latent enthalpy (\(\frac{KJ}{kg}\)) |
| k      | Thermal conductivity of the fluid (\(\frac{W}{m.K}\)) |
| p      | Pressure (Pa) |
| R      | Internal radius of nozzle outlet (mm) |
| S      | Ice Thickness (mm) |
| t      | Time (S) |
| T      | Temperature (\(^\circ\)C) |
| \(v_r, v_z\) | Velocity components near the plate in \(r, z\) directions (\(m/s\)) |
| r, z   | Axisymmetric cylindrical coordinates |
| \(\Delta q\) | Difference in the heat input to the water near the ice and its output (\(\frac{W}{m^2}\)) |
| \(\delta^*\) | Thickness of viscous layer displacement (mm) |

Subscripts

- \(\infty\) Far field
- \(l\) Liquid phase
- \(ls\) Liquid to solid (Phase change)
- \(s\) Solid phase
- \(sub\) Substrate cold plate
1. INTRODUCTION

Freezing is one of the essential phenomena in science and industry. The industry can use the high latent heat of phase change as a reserve. Correspondingly, in semiconductor production, controlling the freezing phase increases the quality of semiconductors, which is also applicable in the nuclear industry. The speed and penetration of ice during the freezing of all kinds of food also plays a significant role in maintaining their quality and shelf life. Ice formation and its conditions on the nose and wings of aircraft and projectiles, such as missiles, must also be carefully assessed. Therefore, a better understanding of this critical phenomenon requires proper and accurate insight into freezing. So far, freezing in the boundary layer has been studied more frequently than freezing in stagnation flow, while a study of both areas is required to complete the study on freezing of a moving object. Many of the few studies on freezing have been conducted in recent years, yet they are significantly valuable. Investigations related to freezing and stagnation flow are: Stefan [1] solved the classic problem of ice formation in polar seas using the analytical method. Goodrich [2] investigated the heat flux of phase change in one-dimensional issues. Sparrow et al. [3] experimentally investigated the behavior of fluid, natural convection in the border of liquid and solid phases. Lacroix [4] considered numerical methods for solving problems of melting the flow of natural convection between two isolated plates. Yeoh et al. [5] investigated a three-dimensional numerical study for free convection with phase change in a cross-section of a rectangular channel. Hadji and Schell [6] investigated combining hydrodynamic with the behavior of the solid-liquid boundary of fluids, which is located between two freezing insulated plates. Hanumanth [7] presented a method for calculating time-dependent heat flux caused by natural convection during freezing fluid between two isolated plates. Curtis et al. [8] provided an integrated model for continuous phase change issues. Trapaga et al. [9] conducted the freezing of molten metal droplets on a rigid plate, and Watanabe et al. [10] conducted a comparison between numerical modeling and laboratory results deformation and freezing of a liquid droplet on a cold plate. Marchi et al. [11] presented an evaluation of an existing model transformation and freezing adjusted to a drop impinging on the substrate plate. Weidman and Mahalingam [12] investigated the flow of viscous fluid produced by the axisymmetric stagnation flow on a flat plate that, at its coordinates, has damped oscillatory motion. Shokrgozar and Rahimi [13] investigated the heat transfer and flow in axisymmetric three-dimensional viscous stagnation flow. They [14] also considered heat transfer and flow in the axisymmetric three-dimensional system with suction and blowing in stagnation flow. They obtained the characteristics of velocity, pressure, temperature and stress in [13, 14] studies. Shokrgozar et al. [15] presented the exact solution of the unsteady heat transfer in stagnation flow on a heated plate. If the common two-phase boundary has uniform heat transfer, the surface of the common boundary will be a flat plate; also, acceleration of the fluid flow is variable in the field of solidification. In this case, the motion of the surface of the common two-phase boundary can be simulated with an accelerating plate towards the flow, so the problem of moving this accelerating plate with variable acceleration must be solved. Also, the minimum thickness of the boundary layer occurs at the maximum value of the plate velocity. The plate velocity Speed plays a significant role in determining boundary layer thickness and acceleration plays a secondary role in the two-dimensional and axisymmetric stagnation flow on an accelerated flat plate [16, 17]. Brattkus and Davis [18] considered stagnation flow solidification of an inviscid fluid that freezes at the shared border, liquid, and solid. Rangel and Bian [19] solved the problem of solidification for inviscid fluid in stagnation flow. Lambert and Rangel [20] investigated freezing in the sub-cooled liquid stagnation region (freezing point) in the two-dimensional
Cartesian coordinate system. Yoo [21] considered viscous fluid phase change in stagnation flow. Shokrgozar and Rahimi [22] presented the solidification of incompressible fluid in two-dimensional stagnation flow. Shokrgozar [23] also showed increasing the Prandtl number up to 10 times or increasing the heat diffusivity ratio up to 2 times leads to a reduction of the ultimate frozen thickness almost by half. While the Stefan number does not affect on the thickness and its effect is captured only on the freezing time in axisymmetric stagnation flow. Alizadeh et al. [24] investigated the steady-state viscous flow and heat transfer in the vicinity of an unaxisymmetric stagnation-point of an infinite stationary cylinder. Adil [25] showed that the magnetic field can reduce the thickness of the velocity boundary layer near the stagnation point flow. Also, increasing the Brownian motion parameter and the thermophoresis parameter cause the thickness of the thermal boundary layer to be smaller than the velocity. In the field of stagnation point flow along with porous medium, Imtiaz et al. [26] investigated the effects of a ferrofluid flow on a variable thicked sheet. The results show the effect of several parameters on speed and temperature. Rahimi and Mozayyeni [27] investigated the unsteady three-dimensional axisymmetric stagnation-point flow of a viscous compressible. Waini et al. [28] showed that the heat transfer rate for the hybrid nanofluid is higher than that of the regular nanofluid as well as the regular fluid in stagnation flow. Also, the nanoparticles and larger Reynolds numbers increase the heat transfer and skin friction coefficients. Shokrgozar and Ghayeni [29] showed the ultimate frozen thickness and the rate of solidification for different values of non-dimensional Prandtl and Stefan numbers for saturated air temperatures in two-dimensional stagnation flow. In the field of stagnation point flow along with magnetohydrodynamics, Narender et al. [30] investigated the effects of radiation in the presence of magnetic field and heat generation/absorption using a Casson nanofluid. Maqbool et al. [31] modeled a ferrofluid stagnation flow over a stretched surface with Ohmic heating and dissipation. The results include the effect of different pertinent flow parameters on temperature, velocity, Nusselt number and skin friction coefficient; however, the aim of this experimental study is to determine the degree to which theoretical findings are consistent with what is happening in practice, and to find a way to determine the flow regime. Note that in the numerical solution, it is assumed that the output flow from the nozzle is fully developed, which is not entirely possible in practice. Of course, we minimize the nozzle length and shape it to minimize the effects of viscosity on the nozzle output to approach the fully developed flow and prevent free jet flow. Also, gravity acceleration causes a slight deviation of stagnation flow. Here, the experimental study can determine the correctness of the assumptions considered in the numerical solution. To this end, a device has been prepared and experiments are carried out on different strains and various distances of the water output section with the cold plate. The results are compared with numerical solutions.

2. EXPERIMENT DESCRIPTION

To conduct the study, a device has been prepared, which is shown in Figures 1a to 1d.

Fig. 1a. Real image of the device used in this Experimental study

Fig. 1b. Schematic of the device and introduction of some of its components

Fig. 1c. Real image of the top of a circular plate on which ice forms (4)

Fig. 1d. Schematic of the circular plate with it fins and a hole where the sensor is installed
It should be noted that the unit of measurement for all temperature measurement equipment and data in this study are degrees Celsius. The device is composed of:

1- A source of the primary water;
2- Primary water pump;
3- Nozzle;
4- Circular plate;
5- The refrigerant inside the insulated tank, containing a mixture of water, ethylene glycol, and liquid nitrogen;
6- Stirring refrigerant pump;
7- Measurements and monitoring equipment, and
8- Filming equipment.

The water, Table 1, in the primary source (1) is supposed to change the temperature in contact with the circular copper cold plate, thereby being cooled by it. This water is pumped (2) upwards by a tube up to a radius R=13mm. At the outlet of the pipe, a nozzle (3) with a radius R=8mm is in the opposite direction to the gravity of the Earth, which emerges vertically on the cold plate. The stagnation flow occurs on the circular copper cold plate. Note that the intention of the nozzle in this paper is merely the output of a tube opening with a length L=18 mm and a constant diameter. The difference in the pipe diameter in the nozzle makes it possible to achieve the minimum formation of a laminar flow profile, which is necessary along with the minimum distance from the nozzle to the cooling plate to avoid free jet flow. The water that does not freeze on the cold plate slips down its sides and exits the circuit. In this case, gravity slightly accelerates water flow after entering the atmosphere and changes its velocity. Note; if the fluid flow is horizontal, the effect of gravity will cause the cylindrical flow to be non-axisymmetric, and we will not have a stagnation flow. The slight effect of gravity, both downward and upward, is equal. Of course, a small change in speed caused by gravity acceleration is one of the factors causing a slight deviation of stagnation flow in the experimental study, which is inevitable. However, when the fluid flow is upwards, the lid of the refrigerant tank can be left open, and ice cubes can be easily seen. It becomes easier to provide refrigerant at -18°C because when the ice cube volume decreased, it immediately maintained the temperature of the fluid by adding liquid nitrogen. Furthermore, it is easier to stir the fluid mixture. In Figures (1c, 1d), the circular plate (4) consists of a heat sink, a heat sensor hole, and a round plate that is made in one piece of copper. The size of the substrate plate obviously has nothing to do with the results. Here, the minimum size is selected so that without the need to produce large amounts of refrigerant, the results are well visible. This plate with a circular cross-section of radius R=9.5 mm on one side, with its fins, is cooled by the refrigerant fluid (5) and, on the other hand, causes water freezing as simple as water cooling. Adding a certain amount of ethylene glycol, antifreeze, can set a particular freezing point temperature for the refrigerant fluid. In this case, a balance is established between solid and fluid. As long as this equilibrium is maintained, i.e. the pieces of ice are floating in the fluid, the temperature of the fluid remains constant at the same temperature. Here the temperature of the refrigerant −18 °C is selected. Therefore, the temperature of the cold plate is very close to −18 °C because the heat transfer coefficient of copper is much higher than that of ice. (Cu: 385 wm⁻¹k⁻¹, Ice: 1.6 385 wm⁻¹k⁻¹)¹ The stirring refrigerant pump (6) uniformizes the temperature of the coolant fluid and increases the heat transfer between the coolant fluid and the circular plate. Measurements equipment and monitoring (7) consist of an inlet water temperature sensor,

¹ Most from Young, Hugh D., University Physics, 7th Ed., Addison Wesley, 1992. Table 15-5.
a circular substrate temperature sensor, an ambient air temperature sensor, a refrigerant temperature sensor and a screen monitor that displays the temperatures. Particular arrangements are predicted for the installation of temperature sensors. An LM35\(^2\) temperature sensor is projected and implemented at the nearest distance to the cold substrate flat plate with the maximum contact coefficient so that their speed and accuracy are maximized. For example, the sensor pod with its diameter has a tolerance of less than 0.5 mm, and the sensor with much force is placed inside the pod. At the same time, silicon paste has been used to fill the probable pores between the pods and the sensor and to increase the maximum contact coefficient. The installation site of this pod inside the copper plate to its surface, which is the place where the water is frozen, is less than 1 mm away. First, the cold plate is stabilized at the desired temperature, and then the water flow pump is turned on. The temperature is measured at each instant, and various desired points, including the inlet water, the refrigerant fluid, the refrigerated substrate plate, the ambient air temperature, and filming is performed at 250 frames per second by the filming equipment (8), a method like a particle image velocimetry, PIV. Note that we do not need to measure speed here because the purpose of this article is to focus on the evolution of ice thickness growth at different times, and this method provides good accuracy for measuring thickness. This speed is fast enough compared to the total time of about 10 minutes, but if the ice level changes are to be considered at the very first moments of the start of ice formation, filming speed will not be enough, no matter how high it will rise, because the speed of freezing at the initial moments is too much. Keep in mind that numerical data [22,24] show the total time of about 10 minutes, and the speed of ice formation at initial moments of 4.5 m/s, which is reduced by a great deal of acceleration.

### Table 1. Water properties at 0 °C

| Property          | Value |
|-------------------|-------|
| Density           | 1000 kg/m³ |
| Specific heat     | 4186 J/(kg·K) |
| Thermal conductivity | 0.6 W/(m·K) |

#### 3. EXPERIMENTAL METHOD

The following steps are followed to conduct the study. First, the nozzle distance is set at a specific value from the surface of the refrigerator plate, and its vertical and central orientation is controlled by the plate as follows. The bottom plate of the nozzle is leveled. With the help of a laser, the three-pin mechanism of the nozzle installation, which includes three adjusting screws, is adjusted so that it is entirely perpendicular to the horizon plane. The water reservoir has an appropriate time in the test environment to allow its water temperature to coincide with ambient temperature. Because the volume of the reservoir is large and its temperature difference with the environment is negligible, the water temperature of the reservoir remains constant until the end of the test. The water level of the tank is maintained constant, which is vital for stabilizing the flow rate. The refrigerant fluid, which contains water and antifreeze, is cooled by liquid nitrogen. Here we add enough antifreeze that at the desired temperature, the water starts to freeze. Adding liquid nitrogen will increase the amount of ice so the refrigerant temperature will remain constant. Conversely, the amount of ice decreases when we heat the refrigerant. So, this two-phase mixture helps to stabilize the temperature of the refrigerant. With this method, the refrigerant temperature remains almost constant, even despite the sudden absorption of heat in the initial moments of the test. So, in the presence of ice, there is sufficient time to increase the amount of liquid nitrogen in the solution, with only a tiny temperature change.

Furthermore, if excess liquid nitrogen is added, more ice will be produced without decreasing the water temperature. The surface temperature of the cold copper plate is reduced to the desired temperature by this two-phase fluid. The copper plate transfers heat from the main water to this refrigerant liquid. Around the copper plate is a PVC\(^3\) plate, and there is no possibility of freezing water in this region. The copper plate is inside the hole in the PVC plate. The copper plate has fins where the refrigerant fluid is, and turbulent flow hits the fins at high speed and cools them. As a result, all

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\(^2\) LM35 is a temperature measuring device having an analog output voltage proportional to the temperature. It provides output voltage in Centigrade (Celsius). It does not require any external calibration circuitry.

\(^3\) A synthetic thermoplastic material made by Polymerizing Vinyl Chloride
temperatures and water flow rates are carefully stabilized, and the results obtained are as accurate as possible. The main pump is then switched on, and water flow is adjusted to a specified value by a globe valve. The turbulent pump flushes the refrigerant liquid flow to provide maximum heat transfer rates. In this experiment, there are two cameras to record. The first camera is turned on for recording, and the focus is set to the cold copper plate. The second camera is responsible for recording temperatures at any moment in order to show the temperature stability. During the test period, temperatures are monitored so that in case of any change, they can be returned to their desired value. When the thickness of ice stops changing, the device is turned off, and the final thickness of the ice is measured. A methyl blue color liquid is used to better observe the ice surface with a meager ratio of 30cc per 100 liters so that the freezing point of the water does not change. In each experiment, films recorded in frame-by-frame are examined, and the thickness of the ice is plotted on a curve in each frame of the note and for each time. The results of the theoretical solution show that the total freezing time is less than 10 minutes, so the freezing of ice thickness is measured at different times. To ensure, if the ice thickness does not change within 15 minutes, the operation will be stopped. Experiments are repeated with different flow rates and different nozzle distances from the flat plate, and the results are recorded.

4. EXPERIMENTAL UNCERTAINTY

Notice the mixture of water, ice, and antifreeze liquid causes the refrigerant solution temperature to remain constant, and the temperature of the water supply is constant. The cooling temperature of the copper plate also is completely under control because the heat transfer rate in copper is so much higher than in water and the test time is so long that temperature changes in the copper surface can be ignored. So, the constant temperature -18°C of refrigerant is about the same temperature of the copper plate. Previously, in Section 2, it was mentioned about keeping the refrigerant temperature constant. The reliability of measuring and calculating are as follows. The sensitivity of LM35 temperature sensors used for measuring is ±0.1°C for the measurement ranges, -18°C to 0°C or 0°C to 8.5°C, so the accuracy is % ± 0.006 and % ± 0.012, respectively. Note that the LM35 temperature sensors are projected and implemented at the nearest distance with the maximum contact coefficient so that their speed and accuracy are maximized. The tolerance of the sensor pod with its diameter is less than 0.05 mm, and the sensor with much force is placed inside the pod. Also, silicon paste has been used to fill the probable pores between the pods and the sensor. Also, in the case of unsteady heat transfer, a contact coefficient generally affects the heat transfer. Here, since the processing time is long (about 15 min), we are dealing with a quasi-steady equilibrium process, so except in the early moments, there is no need to calculate this error. Note that the answers are not acceptable for the first few seconds of startup.

The error caused by the time measuring device is also less than 0.004 seconds (250 frames per second), which will have different errors in the different process stages, initially very high error, and after a few moments, it tends to zero. Therefore again, the error of the time measuring is only significant at the beginning of the process. The data of these initial moments will not be accepted due to the high error.

The ice thickness is measured by magnifying the recorded images at any time and transferring them to AutoCAD software. The error resulting from this measurement is approximately the same as the accuracy of the images less than 0.01 mm. Given the final thickness of ice, 2 mm, the measurement error will be 0.005. Although AutoCAD has a certain image resolution (pixels), the magnification is so high that there is no need to consider its error. Also, the ambient air temperature is stabilized to water temperature (9°C) to minimizing the heat loss from water to the ambient air. Note that the errors are all linear and do not affect each other. All significant errors are summarized in Table 2.

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4 AutoCAD is a commercial computer-aided design (CAD) and drafting software application, developed and marketed by Autodesk.
5. PROBLEM FORMULATION IN NUMERICAL SOLUTION

The governing equations of flow and heat transfer in cylindrical coordinates (for Newtonian, viscous, incompressible, and unsteady flow) are as follows:

Mass:

\[
\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} = 0
\]  
(1)

Momentum:

\[
\frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + v_z \frac{\partial v_r}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial r} + \nu \left( \frac{\partial^2 v_r}{\partial r^2} + \frac{1}{r} \frac{\partial v_r}{\partial r} - \frac{v_r}{r^2} + \frac{\partial^2 v_r}{\partial z^2} \right)
\]  
(2)

\[
\frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + v_z \frac{\partial v_z}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial z} + \nu \left( \frac{\partial^2 v_z}{\partial r^2} + \frac{1}{r} \frac{\partial v_z}{\partial r} + \frac{\partial^2 v_z}{\partial z^2} \right)
\]  
(3)

Unsteady energy equation in the fluid region (dissipation and radiation heat transfer are neglected) reads:

\[
\frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + v_z \frac{\partial T}{\partial z} = \alpha \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right)
\]  
(4)

In solid-phase:

\[
\frac{\partial T}{\partial t} = \alpha_s \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right)
\]  
(5)

With boundary condition at the interface:

\[
\rho h_{ls} \frac{dS(t)}{dt} = k_s \frac{\partial T_s}{\partial S} - k_l \frac{\partial T_l}{\partial S}
\]  
(6)

Notice conductivity and heat capacity coefficient are constant (\(k\) and \(c\) respectively) also \(du \approx cdT\) is assumed where \(p, \rho, \nu, \) and \(\alpha\) are the pressure, density, kinematic viscosity, and thermal diffusivity. Also, subscripts \(s\) and \(l\) denote solid and liquid, respectively.

The numerical solution methods and other boundary conditions of this problem are the same as [24], and the results of this experimental study are compared with [24]. The numerical solution of the problem of water freezing following one of the experimental study scenarios is used to validate the results that so the far field water is at 9 °C, and the cold plate temperature is -18 °C.
6. VALIDATION, PRESENTATION OF RESULTS AND DISCUSSION

First of all, it should be noted that the fluid flow modeled in this experiment can be stagnation flow or a water jet impact a flat plate. In the case of water jets, the heat transfer rate varies in different parts of the plate, while only in the stagnation flow, it is the same for the entire surface of the plate. As a result, in the stagnation flow, the ice thickness will be the same. The preliminary results of this experimental study, Figure 2, and measurements of ice thickness at different points show that the thickness of ice is the same across the entire surface of the plate, so the flow in this experimental study is stagnation flow.

Numerical and experimental results are shown on a graph, in Figures 2 and 3. The numerical solution data according to experimental conditions based on [24] are used in these Figures for comparison. The total results of this laboratory study are also presented in Tables 3, 4, and 5. As shown in Fig. 2, there is a good fit between numerical and experimental results up to the ice thickness of 1.2 mm (point 4, in numerical solution curve, the time range of 1.6 sec). However, in an area beyond the thickness of 1.2 mm, resulting differences are significant. The cause goes back to the nature of numerical and laboratory work. As time passes, the temperature difference between the bottom of the water and the upper ice level decreases. In the numerical solution, this tiny temperature difference causes freezing to continue, although this happens at a low rate. As can be seen, in the thickness of approximately 1.2 mm, the temperature difference in the numerical solution is about 0.022 °C (point 4, in numerical solution curve). However, freezing persists in numerical and experimental studies. At a thickness of 2 mm, the temperature difference in the numerical solution is 0.019 °C (point 6). Here, in the experimental study, freezing has stopped, and this is the point of maximum accuracy of laboratory work. That is, we can say that the accuracy of temperature stabilization is 0.019 °C in the laboratory work. Note that the accuracy of the test does not depend on the accuracy of temperature measurement, but is rather contingent on the stabilization accuracy of flow and temperature. Therefore, although the accuracy of temperature measurement is less than ± 0.1 °C, the precision of the work is higher and continues to a temperature difference of 0.019 °C.

Another point is that due to a tiny temperature difference in a region, points 4-6, the rate of freezing in the laboratory study has decreased compared to the numerical solution. Therefore the significant difference between the two curves is due to the significant increase in freezing time. Note, if freezing continues in laboratory work up to a temperature difference of 0.0001°C (point 7, in numerical solution curve), then the final thickness of the ice is equal in value in numerical and laboratory work, which is impossible. It may also be interpreted as the freezing point using a heat transfer rate. As seen in Fig. 2, freezing is continued to a thickness of 3.75 mm in the numerical solution. However, when ice thickness reaches 2 mm (point 6, in numerical solution curve), the difference in the heat input to the thin water layer near the ice and its output will be less than 3.5 (W/m²). It means that the input heat of the water near the ice is very close to the output heat of that and is not sufficient for freezing the water. In other words, the freezing time increases so much that the amount of heat difference will be smaller than its errors. In these conditions, freezing will practically stop (in the experimental study). Note that $\Delta T$ is the temperature difference between cells of the last row in the ice and the cells of the first row in the water. Also, $\Delta q$ is the difference in the heat input to the water near the ice and its output (W/m²), in numerical solution; however, it can be used as the equivalent temperature and heat input differences for experimental study at any moment.

Fig. 2. Comparing the numerical and experimental results of evolution of ice thickness versus log(time).

Fig. 3. Comparing the numerical and experimental results of freezing velocity of the ice versus log(time)
Table 3. Comparison of numerical and experimental solutions, the evolution of ice thickness parameters.

Table 4. The results of the experiment in a volume flow rate of 2.7 (Lit/Min)

Table 5. The thickness of the ice formed in terms of flow rate and nozzle distance from the substrate cold plate

A comparison between freezing rates of ice in the experimental study and the numerical solution is shown in Fig. 3. It can be seen that these two curves are seemingly not well-matched on the left side of the curve \((\log(\text{Time}) < 0)\). Note, in the experimental study, the freezing rates are obtained by dividing the ice thickness by time, which time in this region is minimal. Consequently, the small error in the denominator causes a significant error in calculating the velocity, so the current matching between the two curves is proper. From the curve, it is observed that the speed of ice formation is very high at first, and then, with a steep slope, the speed of ice formation decreases and then stops. As can be seen, although in the numerical solution of freezing the operation continues up to a very small temperature difference between ice and water, but in practice it is not possible.

In this study, it is clear that the matching of the experiment flow with the stagnation flow is of particular importance. One of the greatest characteristics of a stagnation flow is the uniform heat transfer within the region of this flow. As a result, the fact that the thickness of the ice is the same indicates that the flow is close to the stagnation flow. Here, we use the minimum nozzle distance from the cold plate to find out how close we are to the real stagnation flow. To better understand the problem, the freezing of cylindrical stagnation flow is shown in Figures 4 to 6 schematically. Also, besides the images of results obtained in this study for two distances between the outlet section of water and the substrate plate, Figures 7 and 8, according to ABCD and KLMN regions in Figures 5 and 6, respectively. Notice, to ensure that the entire cylinder is in the radius \(R\) (ABCD region in Figures 4 and 5) resides in the stagnation flow region, a minimum distance between the nozzle and the coolant surface is required. Also, in this Figure, \(\delta^*\) is the thickness of the viscous layer displacement, and in the potential flow, \(\delta^* = 0\). In this case, the nozzle distance to the cooling plate should be at least: \(D_{\text{min}} = R + \delta^*\) (in Fig. 5); otherwise, part of the stagnation flow region will be converted to other fluid flows and the stagnation flow region in this condition would be limited to the KLMN region (Fig. 6) with a radius \(R'\). So the thickness of the ice will not be the same.

Therefore, the constant ice thickness itself is a reason for the existence of a stagnation flow region (Figures 5 and 7). Vice versa, according to the conditions of this experiment, if the thickness of the ice changes on the edges, we are located outside the stagnation flow area, Figures 6 and 8 (i.e., the gap between the nozzle and the plate is too low). Note that the relation \(D_{\text{min}} = R + \delta^*\), which defines the viscous stagnation flow region, is confirmed here using the experimental method. Here, a value of approximately 2.5 millimeters was obtained for the first test.

\[
\delta^* = D_{\text{min}} - R
\]  

(7)

Fig. 5. Minimum distance required for the plate to the nozzle outlet \((D_{\text{min}})\) in the full region of stagnation flow \((R)\).

Fig. 6. Formation of ice when the distance between the plate and the nozzle outlet \((D)\) is less than the minimum required for the complete region of stagnation flow

According to Fig. 6, the thickness of ice is not the same on its entire surface. In Fig. 9, the stages of ice growth are shown for different distances from the nozzle to the cooling plate. One of these distances is \(D = 8\text{mm}\) less than the minimum distance needed to complete the stagnation flow region (related to \(R\).
As can be seen, the graphs match each other with a maximum error of ± 3.5%. Of course, curve $D = 8\text{mm}$ is between the curves $D = 10.5\text{mm}$ and $D = 13\text{mm}$ in the last steps, which is a sign of error in the test. The tiny error is due to the nature of the test; however, the heat transfer across the surface of the cold plate in a laminar or turbulent flow must be the same. So, what is essential is that the final thickness of all distances is the same; because of a perpendicularly impinging flow results in a boundary layer of constant thickness on the substrate. The final thickness of ice versus strain variation is shown in Fig. 10 in which the thickness of ice in the first part of the curve is almost constant and then decreases with a relatively steep slope, and then it returns to constant thickness. However, according to numerical calculations, strain should not affect the heat transfer and freezing of water. So, this steep slope seems to be the result of a transition from a laminar to a turbulent flow. As the strain increases, reaching the turbulent flow region, the thickness of the ice is fixed again. Because there is no particular definition for determining laminar and turbulent regimes in stagnation flow, this test can also be conducted to determine such regimes. Note that strain can be obtained by dividing the velocity of water at nozzle output to $D_{\text{min}}$. The velocity is also obtained by flow rate in each condition. The flow rate is measured by a flow meter in liter/min before the test starts.

Fig. 7. The image of formed ice when the required minimum distance to the plate has been considered. According to Fig. 5, the thickness of the ice is the same on its entire surface.

Fig. 8. The image of formed ice when the required minimum distance to the plate has not been considered.

Fig. 9. Evolution of ice formation for different nozzle distances to the cold plate (the flow rates are all the same)

Fig. 10. Smoothed curve of the formed ice thickness versus variation of fluid strain

7. CONCLUSIONS

In the present paper, an experimental study of freezing in axisymmetric stagnation flow has been investigated. Water impinges vertically on a flat plate and freezes due to the low temperature of the flat plate. For testing, a device has been prepared that includes a cold substrate plate and impinging water modeling with a circular cross-section with the plate. Experiments are carried out on different strains and various distances of the water output section with the cold plate. Comparing the results of this study with numerical solutions displays reasonable and acceptable convergence in the middle of the diagram. Observations show that at first, water starts to freeze rapidly, and then the rate of freezing gradually decreases until it stops. The difference between the two experimental and numerical solutions increases gradually by the increase in ice thickness, because in the experimental study, by reduction of the temperature difference between the ice surface and its adjacent water to about 0.022°C, the freezing rate decreases sharply. Then, at a temperature difference of 0.019°C, freezing has practically stopped. In other words, in this case, the low difference in the heat input to the water layer near the ice and its output is less than its error. So, we can say that the accuracy of temperature stabilization in this experiment is 0.019°C. However, in the numerical solution, freezing continues with a minimal difference up to 0.0001°C, which causes a significant difference of the second half of the two freezing curves, which shows the continuation of freezing observed in the theoretical solution, for tiny temperature differences, is not possible in practice.

As a result, in practice, changes in the thickness of ice indicate a transition to other regimes such as laminar to turbulent flow. Therefore, a particular definition of the flow regimes (laminar, turbulent, or transitional) during the stagnation flow is provided. Interestingly, according to the results, the thickness of ice in the laminar flow is more than one turbulence.
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Figure captions

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Fig. 1b. Schematic of the device and introduction of some of its components
Fig. 1c. Real image of the top of a circular plate on which ice forms (4)
Fig. 1d. Schematic of the circular plate with it fins and a hole where the sensor is installed
Fig. 2. Comparing the numerical and experimental results of evolution of ice thickness versus log(time).
Fig. 3. Comparing the numerical and experimental results of freezing velocity of the ice versus log(time)
Fig. 4. Cylindrical stagnation flow
Fig. 5. Minimum distance required for the plate to the nozzle outlet ($D_{min}$) in the full region of stagnation flow (R).
Fig. 6. Formation of ice when the distance between the plate and the nozzle outlet ($D$) is less than the minimum required for the complete region of stagnation flow
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Table captions

Table 1. Water properties at 0 °C

Table 2. Results of the uncertainty measuring

Table 3. Comparison of numerical and experimental solutions, the evolution of ice thickness parameters.

Table 4. The results of the experiment in a volume flow rate of 2.7 (L/min)

Table 5. The thickness of the ice formed in terms of flow rate and nozzle distance from the substrate cold plate

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Table 1. Water properties at 0 °C

| Property                  | Value     |
|---------------------------|-----------|
| Density                   | 999.88 kg/m³ |
| Kinematic Viscosity       | 1.792*10⁻⁶ m²/s |
| Specific heat capacity    | 4.219 kJ/(kg·K) |
| Thermal conductivity      | 0.561 W/(m·K) |
| Prandtl Number            | 13.67 ----- |
| Latent heat               | 333.55 kJ/kg |
Table 2. Results of the uncertainty measuring

| Variable                              | Uncertainty (%) |
|---------------------------------------|-----------------|
| Plate Temperature ($^\circ$C)         | 0.6             |
| Water Temperature ($^\circ$C)         | 1.2             |
| Time (S)                              | after a few moments : 0.04 |
| Thickness (mm)                        | 0.5             |

Table 3. Comparison of numerical and experimental solutions, the evolution of ice thickness parameters.

| Point No. (Fig. 2) | $\Delta q$ ($\text{w/m}^2$) | $\Delta T_0$ ($^\circ$C) in Numerical Solution | Ice thickness(mm) | $\log_{10}(\text{Time})$ |
|-------------------|-----------------------------|-----------------------------------------------|-------------------|-------------------------|
|                    |                             | Numerical Solution                           | Experimental data |                        |
| 1                  | 1350.1600                   | 0.1861                                        | 0.20              | 0.10                    | -1.2440                |
| 2                  | 91.9520                     | 0.0627                                        | 0.60              | 0.54                    | -0.3819                |
| 3                  | 27.6080                     | 0.0396                                        | 0.94              | 0.94                    | 0.0000                 |
| 4                  | 14.9800                     | 0.0220                                        | 1.20              | 1.17                    | 0.2130                 |
| 5                  | 8.2637                      | 0.0204                                        | 1.50              | 1.30                    | 0.4125                 |
| 6                  | 3.4650                      | 0.0191                                        | 2.00              | 1.50                    | 0.6813                 |
| 7                  | 0.0007                      | 0.0001                                        | 3.75              | 1.90                    | 1.9101                 |
| 8                  | 0.0000                      | 0.0000                                        | 3.75              | 2.00                    | 3.0000                 |

Table 4. The results of the experiment in a volume flow rate of 2.7 (L/min)

| Frame Number | Time (s) | $\log_{10}(\text{Time})$ | Ice thickness (mm) | Velocity (mm/s) | Inlet Water Temperature ($^\circ$C) | Substrate Flat Plate Temperature $T_0$ ($^\circ$C) | Refrigerant Temperature ($^\circ$C) |
|--------------|----------|--------------------------|-------------------|-----------------|-----------------------------------|------------------------------------------------|-----------------------------------|
| 1            | 0.0333   | -1.4771                  | 0.00              | --              | 8.9                               | -23.1                                         | -23.1                             |
| 7            | 0.2333   | -0.632                   | 0.26              | 1.28571         | 9.0                               | -20.1                                         | -21.0                             |
| 12           | 0.4000   | -0.3979                  | 0.49              | 1.37143         | 9.0                               | -20.1                                         | -21.0                             |
| 19           | 0.6333   | -0.1984                  | 0.57              | 0.36735         | 9.0                               | -20.1                                         | -21.0                             |
| 27           | 0.9000   | -0.0458                  | 1.00              | 1.60714         | 9.0                               | -20.1                                         | -21.0                             |
| 44           | 1.4667   | 0.16633                  | 1.11              | 0.20168         | 9.0                               | -20.0                                         | -21.0                             |
| 64           | 2.1333   | 0.32906                  | 1.23              | 0.17143         | 9.0                               | -20.0                                         | -21.0                             |
| 82           | 2.7333   | 0.43669                  | 1.31              | 0.14286         | 9.0                               | -20.1                                         | -21.0                             |
| 98           | 3.2667   | 0.5141                   | 1.34              | 0.05357         | 9.0                               | -20.1                                         | -21.0                             |
| 115          | 3.8333   | 0.58358                  | 1.37              | 0.05042         | 9.0                               | -20.0                                         | -21.0                             |
| 130          | 4.3333   | 0.63682                  | 1.40              | 0.05714         | 9.0                               | -20.0                                         | -21.0                             |
| 147          | 4.9000   | 0.6902                   | 1.49              | 0.15126         | 9.0                               | -20.1                                         | -21.0                             |
| 162          | 5.4000   | 0.73239                  | 1.57              | 0.17143         | 9.0                               | -20.1                                         | -21.0                             |
| 173          | 5.7677   | 0.76092                  | 1.60              | 0.07792         | 9.0                               | -20.0                                         | -21.0                             |
| 195          | 6.5000   | 0.81291                  | 1.57              | -0.03900        | 9.0                               | -20.1                                         | -21.0                             |
| 211          | 7.0333   | 0.84716                  | 1.57              | 0.00000         | 9.0                               | -20.1                                         | -21.0                             |
| 289          | 9.6333   | 0.98378                  | 1.60              | 0.01099         | 9.0                               | -20.0                                         | -21.0                             |
| 335          | 11.1667  | 1.04792                  | 1.60              | 0.00000         | 9.0                               | -20.1                                         | -21.0                             |
| 384          | 12.8000  | 1.10721                  | 1.63              | 0.01749         | 9.0                               | -19.6                                         | -21.0                             |
| 427          | 14.2333  | 1.15331                  | 1.66              | 0.01993         | 9.0                               | -19.6                                         | -21.0                             |
| 472          | 15.7333  | 1.19682                  | 1.71              | 0.03810         | 9.0                               | -19.6                                         | -21.0                             |
| 622          | 20.7333  | 1.31667                  | 1.74              | 0.00571         | 9.0                               | -19.7                                         | -21.0                             |
| 772          | 25.7333  | 1.4105                   | 1.77              | 0.00571         | 9.0                               | -19.8                                         | -21.0                             |
| 922          | 30.7333  | 1.48751                  | 1.80              | 0.00571         | 9.0                               | -19.9                                         | -21.0                             |
| 1072         | 35.7333  | 1.55307                  | 1.83              | 0.00571         | 9.0                               | -19.9                                         | -21.0                             |
Table 5. The thickness of the ice formed in terms of flow rate and nozzle distance from the substrate cold plate

| Test No. | Nozzle Distance from Substrate (mm) | Flow Rate (Lit/Min) | Strain (l/s) | Maximum Ice Thickness, $S_{max}$ (mm) | Substrate Flat Plate Temperature, $T_p(\degree C)$ | Water Temperature, $T_i$ |
|----------|-----------------------------------|--------------------|--------------|--------------------------------------|---------------------------------|-----------------|
| 1        | 8                                 | 2.7                | 8.57         | 2.0                                  | -19.7                          | 9.1             |
| 2        | 8                                 | 3.5                | 18.36        | 2.0                                  | -19.3                          | 8.5             |
| 3        | 8                                 | 4.2                | 26.06        | 1.8                                  | -19.0                          | 8.2             |
| 4        | 8                                 | 4.4                | 27.97        | 1.7                                  | -19.0                          | 8.4             |
| 5        | 10                                | 4.4                | 23.60        | 2.2                                  | -19.8                          | 8.3             |
| 6        | 10                                | 4.5                | 18.59        | 2.1                                  | -19.6                          | 8.5             |
| 7        | 10                                | 5.1                | 23.86        | 2.0                                  | -19.0                          | 8.4             |
| 8        | 10                                | 6.8                | 38.50        | 1.8                                  | -18.5                          | 8.4             |
| 9        | 13                                | 4.0                | 6.49         | 2.4                                  | -19.8                          | 9.1             |
| 10       | 13                                | 5.0                | 11.51        | 2.2                                  | -19.9                          | 8.7             |
| 11       | 13                                | 5.4                | 14.02        | 2.0                                  | -18.6                          | 7.9             |
| 12       | 13                                | 6.1                | 18.69        | 2.0                                  | -19.8                          | 9.2             |
| 13       | 13                                | 8.4                | 33.74        | 1.9                                  | -18.9                          | 8.4             |

A brief technical biography:

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