

**AN EXPERIMENTAL RESEARCH ON THE EFFECTS OF
FROST FORMATION ON DIFFERENT ENVIRONMENTAL
CONDITIONS AND SURFACE CONFIGURATIONS**

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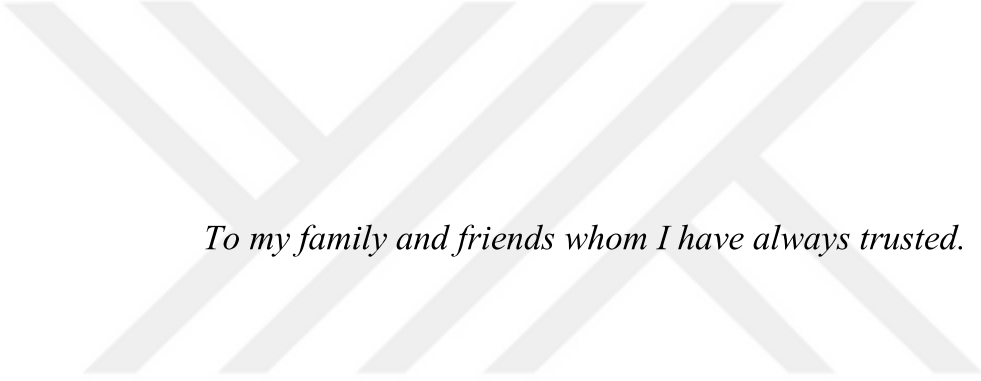
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To my family and friends whom I have always trusted.

ABSTRACT

Frost formation on finned surfaces is observed on heat exchangers in cooling systems such as refrigerators and air conditioners. Accumulated frost on finned surfaces blocks the air flow in between fins and reduces the effective surface area and it creates an additional resistance for heat transfer. The frost accumulation on finned surfaces increases the energy consumption of a cooling system and needs to be mitigated by the design of the finned surfaces. In this experimental study, the effects of air velocity, relative air humidity, surface temperature, fin length, fin space, surface orientation and surface coating on the heat transfer performance of the finned surface have been investigated. The measurements were conducted in a horizontal wind tunnel open to atmosphere. Air at 18 °C was used over temperature controlled cold finned surfaces positioned inside the test section of the tunnel. The heat transfer rate through the finned surface was measured during the experiment using an in-house built Heat Flux Measurement System (HFMS). Experiments showed that frost accumulation on finned surfaces blocks the air penetration into fin gaps and results in a sharp drop in the heat transfer rate. It has been found that high relative humidity, high incoming air velocity, high fin length increases the heat transfer rate from the finned surface by reducing the negative impact of frosting on the heat transfer rate. Condensed water droplets occur on the surfaces since higher parameter values provides higher heat transfer rates. Condensed water droplets turn to ice with the beginning of the frost formation. High thermal conductivity of ice increases the effective thermal conductivity of frost and provides higher heat transfer rates. Narrow fin space is found to be disadvantageous under the frosting conditions. The small gap between fins is easily blocked by the frost and the effective surface area of the finned surface is heavily reduced. Fin gaps larger

than 4 mm are required if the surface is to be used under frosting conditions. The effect of different fin shapes has also been studied. Knife edge shaped fins are found to be better in terms of heat transfer rate as compared to staggered and inline type fins. Regarding the orientation of the finned surface with respect to air flow, it was found that the parallel flow arrangement results in the highest heat flow rate compared to the impinging flow arrangement. This is due to the fact the finned surfaces under parallel flow arrangement is subjected to less frost accumulation. Finally, the effect of the superhydrophobic coating on the heat transfer performance of the finned surface was studied. The coated surfaces do not have a significant amount of water condensation in the vertical orientation and also in the parallel flow arrangement. On the other hand, over the uncoated surface considerable amount of water condensation was found. It could be that the water droplets could not adhere to the coated surface because of the superhydrophobic coating. The absence of the water droplets on the coated surface resulted in an earlier frost growth which resulted in an earlier blockage of the fins and an earlier drop in the heat transfer rate. Finally, the measurements have shown that hydrophobic coatings show a negative impact on the heat transfer rate of the finned surfaces under impinging flow conditions.

ÖZET

Buzdolapları ve klimalar gibi soğutma sistemlerinin ısı değiştiricileri üzerindeki kanatlı yüzeylerde kar oluşumu incelenmektedir. Kanatlı yüzeyler üzerinde oluşan kar kanatlar arasındaki hava akışını engeller ve efektif yüzey alanını azaltır. Bu aynı zamanda ısı transferi için ekstra direnç oluşturur. Kanatlı yüzeylerdeki kar birikimi soğutma sistemlerinin enerji tüketimini arttırdığından bunun kanatlı yüzey tasarımıyla azaltılması gerekmektedir. Bu deneysel çalışmada hava hızı, bağıl nem, yüzey sıcaklığı, kanat uzunluğu, kanat boşluğu, yüzey oryantasyonu ve yüzey kaplamasının kanatlı yüzeylerin ısı transfer performansı üzerindeki etkileri araştırılmıştır. Ölçümler atmosfere açık yatay bir rüzgar tüneline yürütülmüştür. 18 °C sıcaklığındaki hava tüneline deney bölgesinin içine yerleştirilen sıcaklık kontrollü soğuk yüzeye gönderilmiştir. Kanatlı yüzey boyunca ısı transfer hızı, deney sırasında dahili bir Isı Akışı Ölçüm Sistemi (HFMS) kullanılarak ölçülmüştür. Deneyler, kanatlı yüzeylerde kar birikmesinin kanat boşluklarına hava girişini engellediğini ve ısı transfer oranında keskin bir düşüşe neden olduğunu göstermiştir. Yüksek bağıl nem, gelen hava hızı, kanat uzunluğunun kanatlı yüzeyden ısı transfer hızını arttırdığı ve ayrıca karlanmanın ısı transfer hızı üzerindeki olumsuz etkisini sınırladığı tespit edilmiştir. Dar kanat boşluğu buzlanma koşulları altında dezavantajlı bulunmuştur. Kanatlar arasındaki küçük boşluk, kar tarafından kolayca bloke edilir ve kanatlı yüzeyin etkin yüzey alanı büyük ölçüde azalır. Eğer yüzey karlanma koşulları altında kullanılacaksa kanat boşluğunun 4 mm'den daha geniş olması gerekmektedir. Farklı kanat şekillerinin etkileri çalışılmıştır. Bıçak kenarı şekilli kanatlarında kademeli veya sıralı kanatlarla karşılaştırıldığında daha iyi ısı transfer hızı olduğu bulunmuştur. Kanatlı yüzeyin hava akışına göre oryantasyonu ile ilgili olarak, paralel akış düzenlemesinin, çarpan akış düzenlemesine kıyasla en

yüksek ısı akış hızına sahip olduğu bulunmuştur. Bunun nedeni, paralel akış düzenlemesi durumunda kanatlı yüzeylerde daha az kar birikimine maruz kalması olabilir. Son olarak, süperhidrofobik kaplamanın kanatlı yüzeyin ısı transfer performansı üzerindeki etkisi incelenmiştir. Kaplanmış yüzeyler, kanatlı yüzeyin dikey düzenlemesinde ve ayrıca paralel akış düzenlemesinde yüzey üzerinde önemli ölçüde su yoğunlaşmasına maruz kalmamıştır. Ancak kaplanmamış yüzeyde önemli miktarda su yoğunlaşması tespit edilmiştir. Süperhidrofobik kaplama nedeniyle su damlacıklarının kaplanmış yüzeye yapışmaması olabilir. Kaplanmış yüzey üzerinde su damlacıklarının olmaması, kanatların daha erken tıkanmasına ve ısı transfer oranında daha erken bir düşüşe neden olan daha erken bir kar büyümesine neden oldu. Bu nedenle, tüm ölçümler, hidrofobik kaplamaların, çarpan akış koşulları altında kanatlı yüzeylerin ısı transfer hızı üzerinde olumsuz bir etki gösterdiğini göstermiştir.

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Nomenclature

A	Surface area [m ²]
$HFMS$	Heat flux measurement system
k	Thermal conductivity [W/m-K]
k_{al}	Thermal conductivity of aluminum [W/m-K]
k_{glass}	Thermal conductivity of glass [W/m-K]
L	Fin length [mm]
L_c	Characteristic length [mm]
R_{cond}	Conduction thermal resistance [K /W]
Re	Reynolds number [$Re=V_{air}L_c/\nu$]
RH	Relative humidity [%]
s	Fin space [mm]
t	Thickness [m]
t_{al}	Thickness of aluminum [m]
t_{glass}	Thickness of glass [m]
T_{air}	Air temperature [°C, K]
T_{set}	Set temperature [°C, K]
T_l	Temperature of Aluminum-3 [°C]
V_{air}	Air velocity [m/s]
ω_A	Error rate in surface area [%]
$\omega_{\dot{Q}}$	Error rate in heat flow rate [%]
$\omega_{\dot{Q}_{fin}}$	Error rate for finned surface heat flow rate [%]
$\omega_{\dot{Q}_{unfin}}$	Error rate for unfinned surface heat flow rate [%]
$\omega_{\Delta T}$	Error rate for temperature difference [%]

$\dot{Q}_{fin}$	Heat transfer rate of finned surface [W]
$\dot{Q}_{unfin}$	Heat transfer rate of unfinned surface [W]
ΔT	Temperature difference [K]
z	z-axis of the coordinate system
ϑ	Air kinematic viscosity [m ² /s]



CHAPTER I

INTRODUCTION

Frost accretion is commonly seen at large number of cooling systems. Warm moist or humid air upon contact with a cooled surface results in frost on the surface. The accumulated frost causes insulation between the air and the cold surface. The frost layer increases thermal resistance and the energy consumption of systems such as refrigerators, freezers, air conditioners [1,2,3]. Liu et al [4] indicated in their study, frost accumulation increases the energy consumption of refrigerators by 20%. Considering that 14% of the residential energy consumption of world belongs to freezers and refrigerators, it is understood that this increase is too much [5]. Because of that, researchers have studied frosting problems in cooling systems. The frosting is a complex process and researchers started with an understanding of frost structure. Frost constitutes isolation effects due to its structure, which is one of the main reasons for energy consumption increases of the cooling systems. The reduction of air pressure drop is one of the other negative effects of frost formation. However, this study is focused on the thermal effects of frost formation. The effects of icing occurring on different surfaces on heat transfer were investigated to understand the negative effects. Thermal conductivity, heat transfer coefficient, porosity and thickness of frost investigated by researchers. First, studies on frost accumulation on flat surfaces under different flow conditions were carried out, then researchers focused on the frosting on the surfaces of heat exchangers. Heat exchangers are used to cool the air in refrigeration systems, so for industrial applications, studying frosting on a heat exchanger is a more realistic approach. All studies aimed to understand frost properties and effects on heat transfer

for different environmental conditions and develop anti-frosting methods. Surface treatment methods, ultrasound waves, different environmental conditions, different surface cooling methods etc. have been investigated. However, there is not an exact method to prevent frost accretion or maximize the system performance. Because of that, researchers started to investigate the most effective solution to decrease frost formation on the surfaces. For example, Kerpici et al [6] presented an exact method to obtain maximum efficiency for the systems, does not exist therefore, an optimum value has to be found out. They only presented a limited number of methods to mitigate or predict frost accumulation.

Frost accumulation starts with condensation. Condensed water droplets start to grow and freeze while frozen droplets form a so-called branch. Piucco et al [7] show this process in Figure 1. Frost thermal conductivity is found to be around 0.2 W/m-K [7]. The low thermal conductivity of frost reduces the heat transfer between the surface and the air. In addition, the air trapped between branches increases thermal resistance between air and surface. This explains the significant effect of frost accumulation on heat transfer from/to the surface.

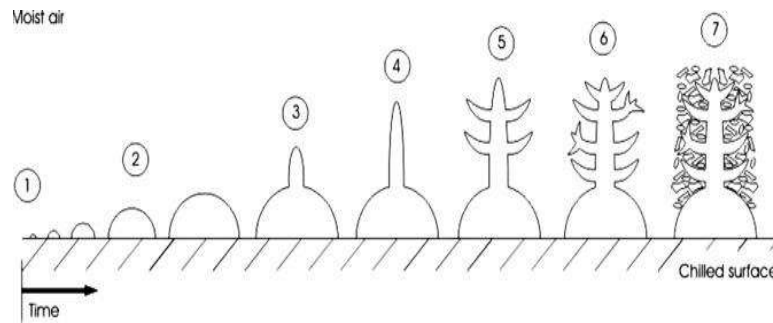


Figure 1. A step by step growth of a frost embryotical growth [7].

In this study, experiments have been done to understand the effects of relative humidity, air velocity, fin length, fin space, fin types, alignment, angle of attack and

coating on frost formation for impinging flow. Finned surfaces have been chosen to increase heat transfer between the surface and air and this provided to observe frost formation effects on heat transfer. In the next section, some works of literature are explained in detail to understand the main effects of freezing propagation on heat transfer. Different surface and environmental conditions have been investigated to understand frost formation behaviour for different conditions. This extensive study aims to provide simplify frosting behaviour for practical applications.

Studies of other researcher have been investigated detailly in Chapter II. Chapter III explained the experimental conditions, detailed explanation of test setup, equipment, uncertainty calculation, surface types and measurement technique of heat flow rate, frost thickness and temperature. Test results analysed in Chapter IV. Outcome of this study epitomized in Chapter V. Chapter VI gave some suggestions for next studies.

CHAPTER II

LITERATURE REVIEW

Frost thickness has vital importance for frost accumulation due to its high effect on heat transfer. Higher frost thickness means more trapped air between the frost branches leading to a reduction in heat transfer. On the other hand, frost density is another main parameter for frost accumulation and heat transfer between a surface and air. But, frost density and thickness show opposite behaviour to each other. Thus, controlling these two properties of the coolant (air in this study) has the biggest importance to achieve the desired heat transfer. The effects of air velocity, temperature, humidity, and surface temperature parameters especially on the frost thickness have been investigated in the current study.

Cheng and Wu investigated [8], the frost thickness variation under different air velocities (2-13 m/s), air temperatures (20-35 °C), relative humidity levels (40-80%) and surface temperature (-13- -2 °C) on a cold plate. There, they did not observe a significant effect of air temperature and velocity on the frost thickness. But, reducing the thermal resistance of the frost has shown a multiple step ascending pattern of the frost layer, which happens at 3 steps as melting, freezing and frost formation. Moreover, these steps cause an increase in the density of the frost. In this study, the frosting was investigated on the finned surface at similar environmental conditions. There, the results of this study showed that the air velocity had an important effect on frost thickness at horizontal orientation.

On the other hand, Chen et al [9] compared a numerical model with experimental data for frost formation on a horizontally oriented plate at 3 different air velocities and surface temperatures. It is presented that the effects of air velocity on

density are much more dominant than the frost thickness. Moreover, they had enlarged their study by investigating the heat transfer changes with relative humidity on finned surfaces too.

Again the frost accumulation relations with almost similar environmental conditions (1 to 4 m/s, 5 to 16 °C, 50 to 80% RH and -25 to 0 °C) have been studied for a flat plate by Leoni et al [10]. Their results show that the frost thickness increases with decreasing air temperature, higher temperature differences between air and cold plate surfaces and high air humidity [10]. They also investigated the same case but with different surface types.

In another study, Chen et al [11] investigated the pressure effects (0.1, 0.5 and 1 Bar) on the frost accretion process for a flat plate. This study clearly showed that a thinner frost layer took place under lower atmospheric pressure.

However, some other experimental parameters such as air temperature (5 to 20 °C), Re number (1000 to 3000), surface temperature (-20 to -10 °C) and air humidity ratio (0.003 to 0.0055 kg/kg_{da}), and their effects on the frost accumulation on the vertical plate have been investigated by Lee and Ro [12]. The experiments show that higher air humidity causes higher frost thickness. Moreover, the effects of relative humidity on frost thickness were investigated for vertically positioned finned surfaces. Their results showed that the relative humidity effects also depended on the initial frost thickness of measurements and surface temperatures.

Hermes et al studied [13] the frost thickness and heat flux changing with surface temperature (-30 to 0 °C) on a flat surface. Results proved that the higher heat flux values due to higher temperature differences between air and surface temperatures cause a thicker frost layer. Moreover, the surface temperature effects on the heat flow rate of

frosting conditions were investigated that were presented in their study with similar effects of surface temperature.

Another focus was done by Zhang et al. [14] who conducted frost accumulation experiments on a flat surface to show that frost thickness and roughness varied on the flat surface according to the frost crystal types. In their study, it was observed that higher air velocity and humidity also lower surface and air temperatures had an increasing effect on frost thickness.

Surface inclination effects on the frost formation for a flat plate have also been studied by Kim et al [15]. They have presented the reason for the change of the thickness and density according to the surface inclination angle in Figure 2.A. The figure shows the dispersion and turn back to the surface movement of the frost particles, while B shows the scattering from the surface at the horizontal condition which provides information about thickness increase due to mass decrease. In this study, finned surfaces oriented through to gravitational direction were used and the accumulated frost layer was visualized.

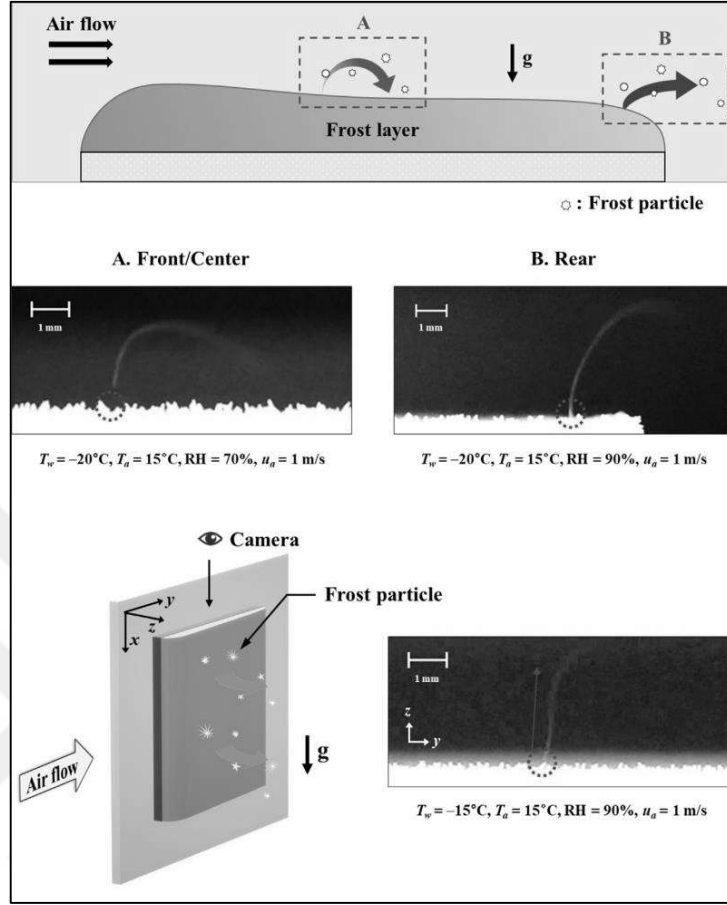


Figure 2. Behaviours of a frost particle [15].

Ren et al [16] have observed the frost layer growth rate behaviour for three different finned tube sections which are flow boiling, liquid-phase forced convection, and gas-phase forced convection section. There the maximum frost thickness has been observed in the FB section due to flow boiling.

However, Liu et al [17] have worked to observe the effects of surface types on the frost accumulation on a vertically positioned flat plate. There was 4-5 minutes difference at the first frost deposition between hydrophilic and hydrophobic surfaces. While hydrophobicity and hydrophilicity do not show any differences in the frost thickness, the superhydrophobic coated finned surface was compared to the uncoated finned surface for different air velocities and orientations in this study.

Adanur et al [18] have used horizontally positioned aluminium, hydrophobic, hydrophilic, and three biphilic flat plate surfaces to investigate frost growth and nucleation for forced convection. Average frost thicknesses of hydrophobic and hydrophilic surfaces showed a similar trend to biphilic surface 1. Hydrophobic, biphilic 2 and 3 surfaces presented same frost thickness trend. Aluminum surface showed the biggest frost density. Frost thickness uncertainties at the start of the frost accumulation cause fluctuations in the density. Figure 3 shows the biphilic surface structure.

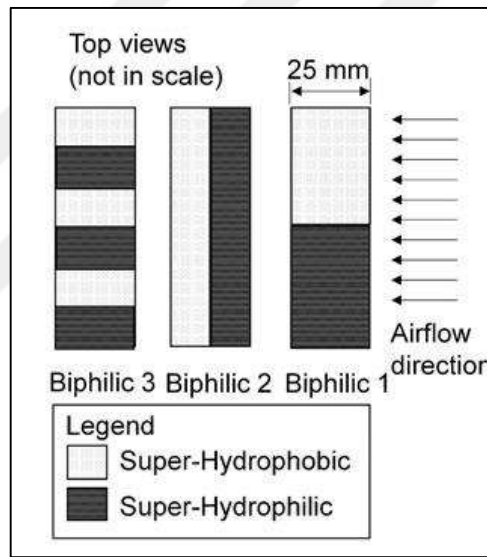


Figure 3. Surface types of Adanur [18].

Heat transfer performance changing with perforated fin tube heat exchangers for frost accumulation has been studied by Liu et al [19]. Air inlet temperature and relative humidity settled up to 5 °C and 60%, respectively. Experiments have been done for different fin pitches. The heat flow rate reduction of the 20 mm fin space was higher than the 5 mm fin space condition and then occurred. Fin tube heat exchangers are shown in Figure 4.

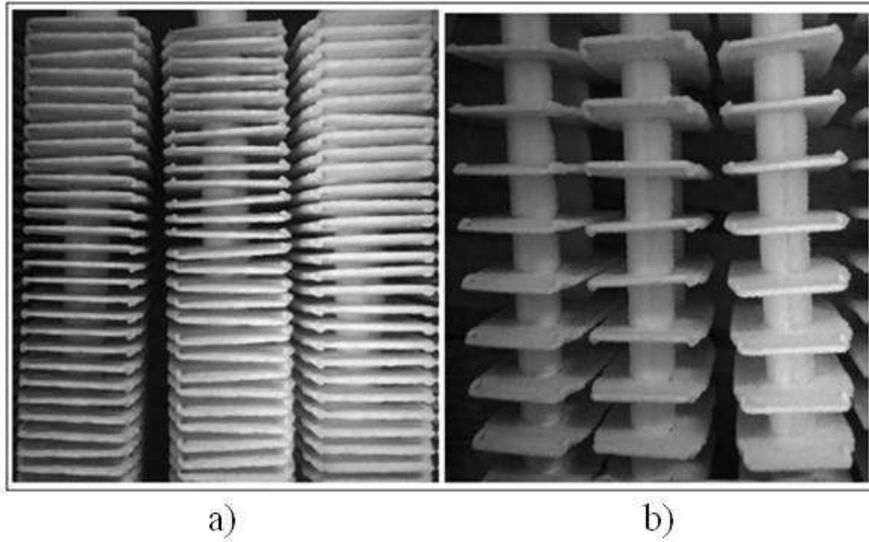


Figure 4. Frost formation on heat exchanger surfaces with different fin spaces a) 5 mm
b) 20 mm [19].

Chung et al [20] have been investigated the frost accumulation process for an air source heat pump. They showed higher heat transfer performance was shown for the higher air velocities. This study is shown that the rising of air velocity increases the heat transfer rate.

Amini et al [21] the effects of different mean refrigerant temperatures, different air temperature and different humidity conditions under natural convection were examined in the tube and fin heat exchanger. Lower refrigerant means temperature causes quicker frost growth rates with thicker frost thicknesses. Air temperature changes show different effects on the frost thickness and frost growth rate. When the air temperature rises from 20 °C to 25 °C thickness and growth rate go up. However, thickness and growth rate show opposite behaviour when the temperature increased from 25 °C to 30 °C, seen in Figure 5. Air temperature and relative humidity are the highest influencer parameters for frost growth rate. Frost propagation started on fin tips then covered the fin spaces. It provided higher heat transfer performance for a longer

time. In this study finned surfaces investigated at horizontal, vertical and parallel orientation. Fin spaces closed by frost in vertical and parallel orientation similarly.

Time	$t = 0$ h	$t = 2$ h	$t = 4$ h	$t = 6$ h	$t = 8$ h	$t = 10$ h	Rate of frost growth (mm/hr)
$T_a = 20^\circ\text{C}$	0	2.14	3.59	3.99	4.74	5.09	0.51
$T_a = 25^\circ\text{C}$	0	3.27	4.66	5.49	6.33	6.95	0.69
$T_a = 30^\circ\text{C}$	0	2.69	4.10	4.92	5.54	6.05	0.61

Figure 5. Frost thickness for different air temperatures [21].

The changing frosting behaviour of horizontally positioned hydrophilic and hydrophobic flat surfaces with wettability under forced convection conditions was studied by Hermes et al [22]. There is accumulated frost on the surface at $t=0$. Reynolds number is not an important factor for frost thickness. Velocity has very a small effect on frost growth.

Frost deposition effects on heat transfer of a tube bank have been studied by Hernandez et al [23]. Frost thickness differences are smaller than 1% for maximum and minimum Reynolds number. High Re number provides more uniform frost accumulation on the surface.

The fin spaces of the fin tube heat exchanger were modified by Zhang et al [24] to observe the frost deposition behaviour. Experimental conditions were 0°C to 4°C air temperature, 65% to 85% relative humidity, 1.2 m/s to 2.4 m/s air velocity and evaporating temperature -10°C . Fin space differences of FTHX 1 (2 mm fin space) and FTHX 2 (3.2 mm fin space) are the main reason for the frost thickness differences at the same frosting conditions. Smaller fin spaces cause less heat transfer and moisture in the air flow during the frost accumulation process. FTHX 1 has bigger frost thickness differences at the entrance to windward fins and the exit from LFR than FTHX 2 for different frost accumulation conditions. In FTHX 2, the higher heat and humidity that

passes through the airflow between the two fins, resulting in a smaller drop in freezing rate than FTHX 1.

Sommers et al [25] investigated frost thickness for hydrophobic and hydrophilic flat surfaces under natural convection conditions. Hydrophobic surface has a thicker frost thickness than the baseline surface and hydrophilic surface. Coated finned surface experiments compared to uncoated finned surfaces and thicknesses of the coated surface were thicker than the uncoated finned surface in this study.

Li et al [26] study investigated the ultrasound effect on the frost nucleation for the flat plate under natural convection. Ultrasounds decrease frost thickness up to 75%. Ultrasound effects decrease the frozen droplet sizes. The branch of the frozen droplet cannot be seen in this situation.

Wang et al [27] studied the electric field effect on frost accumulation for fins under natural convection. Electrodynamic effects provide thinner branches at accumulated frost and gravity break off these thin branches. However, they indicate only positive polarity decreases the frost thickness, negative polarity affects the thickness oppositely.

Effective thermal conductivity of frost was investigated for the flat plate under different humidity ratios, Re number, air temperatures and plate temperatures conditions by Sahin [28]. Frost thermal conductivity increased with the rise of Re number. The denser frost layer showed higher effective frost thermal conductivity.

The thermal density of frost was investigated study of Fukusako [29]. Density is a very important parameter for their thermal conductivity. Raising the density increases the thermal conductivity.

Huang et al [30] studied the conditions of frost accumulation under forced convection on the horizontally positioned flat surface. Thicker frost thickness is seen at lower surface temperature and higher relative humidity. Air temperature increases frost thickness until the temperature reaches the critical value.

Ye and Lee [31] investigated a model to predict air flow decreasing in the fin and tube heat exchanger performance of air source heat pumps due to frost build-up. Denser frost occurs at high air velocities leading to a rise in the pressure loss coefficient. Temperature differences between a cold surface and a frost surface increasing cause more water vapor absorption. Denser frost accumulates with this process. All of them are the result of higher air velocities. This denser frost layer has a higher blockage effect on the air flow due to less porosity on the frost layer. Experiments show pressure loss coefficient has not been affected by humidity. This shows frost density does not change with humidity.

Shen and Wang [32] have studied frost porosity on a flat plate under forced convection conditions. 1 and 0 values for porosity define pure air and pure ice, respectively. Dielectric constant rises from 7 to 53 when the porosity slightly decreases to 0. However, the drop at the porosity is very quick from 1 to 0.6 when the dielectric constant around 7.

Huang et al [33] have investigated the effects of fin space and different fan types on heat transfer performance variation with the increase of frost thickness for a finned plate tube heat exchanger. Higher fin space caused heat flow rate reduction. They did not report major heat transfer performance differences between axial and centrifugal fans for large fin spaces.

Liu and Kulacki [34] found that the superhydrophobic surface shows a superior characteristic during a defrost process than superhydrophilic and plain surfaces. It was also shown that frost nucleation is independent of the contact angle when the contact angle of droplets is higher than 140° .

Oksuz et al. [35] investigated the change of heat transfer rate during frost propagation on vertically aligned, finned surfaces under impinging flow conditions. It has been reported that there is no significant variation in the heat transfer rate after the fins are completely covered with a layer of frost.

Lee and Yang [36] investigated that the early stages of frost formation on a cold plate. They observed a quicker heat transfer rate decreasing at the initial period of frost propagation than in later stages.

Air quality effects on the supercooling degree and freezing time have been investigated on a flat plate by Gong et al [37]. The results showed that most of the solutions were able to increase the supercooling degree and speed up the freezing process.

Heat transfer coefficients and total conductivity of fin and tube heat exchangers under forced convection conditions were investigated for the frost formation process in Seker et al [38]. Results showed that frost thickness and total heat transfer coefficient increase with air inlet temperature rising. This agrees with Rite's [39]. However, Kondepudi [40] shows that after a while UA has started to decrease.

Three different types of heat exchangers performance have been investigated for different air velocity and humidity at dry, wet and frost accumulation conditions in Zhang and Hrnjak [41]. Parallel flow plate fin and serpentine fin had the highest

refrigeration performance. However, frost accumulation on them increased the air pressure drop by 5 times.

Na and Webb [42] have investigated parameters, which affect frost nucleation. They have found that the frost formation nucleation stage depends on thermodynamic principles. The necessity of supersaturation degree increased with lower energy surfaces.

Song et al [43] investigated water droplet freezing process. They showed water droplets turn to opaque when they are frozen (see in Figure 6). Temperature increase was also observed at the freezing stage of water droplets as seen in Figure 7.

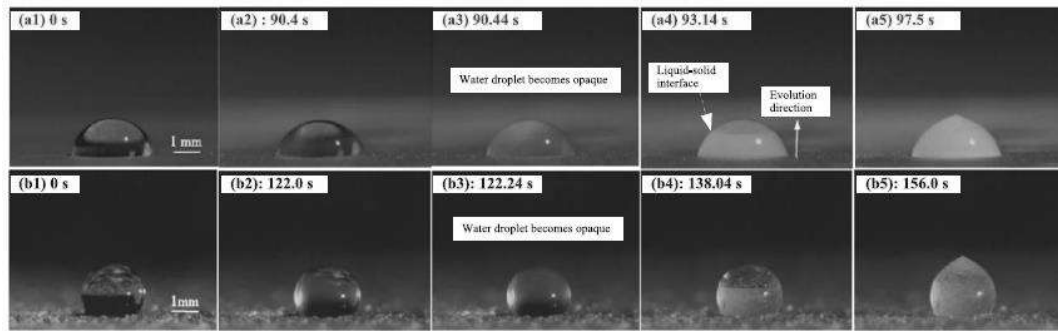


Figure 6. Frozen water droplets turning to opaque [43].

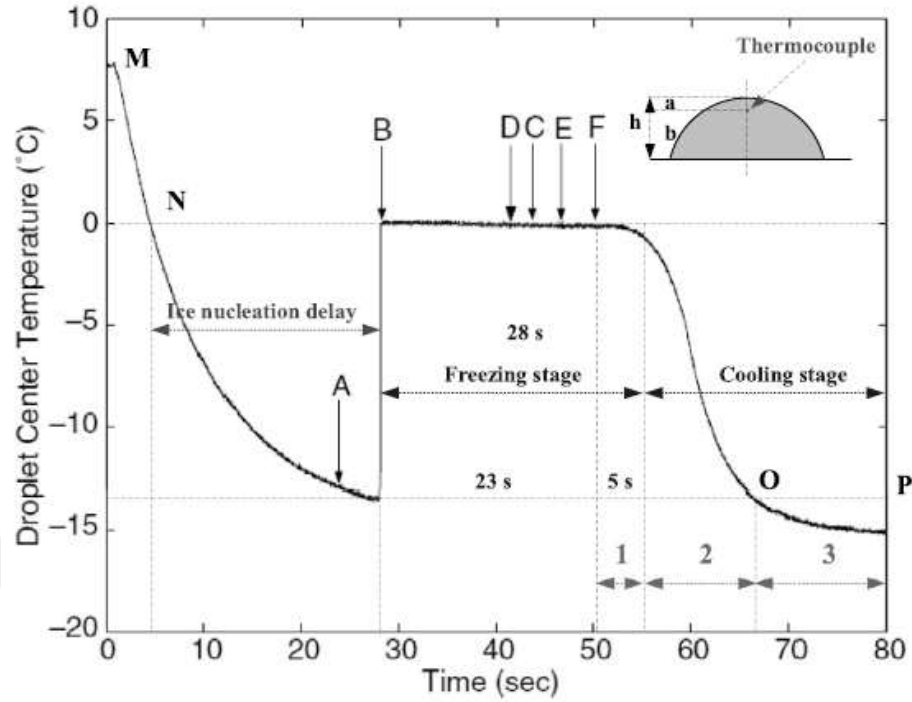


Figure 7. Temperature change during freezing stage of water droplets [43].

There is a contradiction among literature for air velocity effects on frost formation. Literature has been investigated air velocity, air temperature, air humidity, surface temperature, coating and fin spaces effects on frost thickness, heat transfer, density and thermal conductivity for different surface and heat exchanger types. Effects of different finned length, fin types, orientation, and angle of attack effects on heat transfer rate, and frost thickness for frosting conditions under impinging flow conditions have been investigated distinctly. However, impacts of air velocity, relative humidity and fin space on heat transfer rate, and frost thickness have been investigated.

CHAPTER III

EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

3.1 Wind Tunnel, Peripheral Devices, and Test Section

An open-loop wind tunnel has been designed to investigate frost formation on different surface types as seen in Figure 8. Galvanized sheet metal has been used to produce the tunnel. The entrance of the tunnel is $600 \times 600 \text{ mm}^2$ and the diameter of the tunnel exit is 600 mm. A suction fan (560 mm in diameter) was positioned at the end of the tunnel to provide forced convection conditions. The fan was regulated by an inverter to adjust air velocity inside of the tunnel. Air flow was straightened by a honeycomb. The honeycomb is made up of pipettes and was positioned at the entrance of the tunnel. The honeycomb is made up of pipettes and was positioned at the entrance of the tunnel.

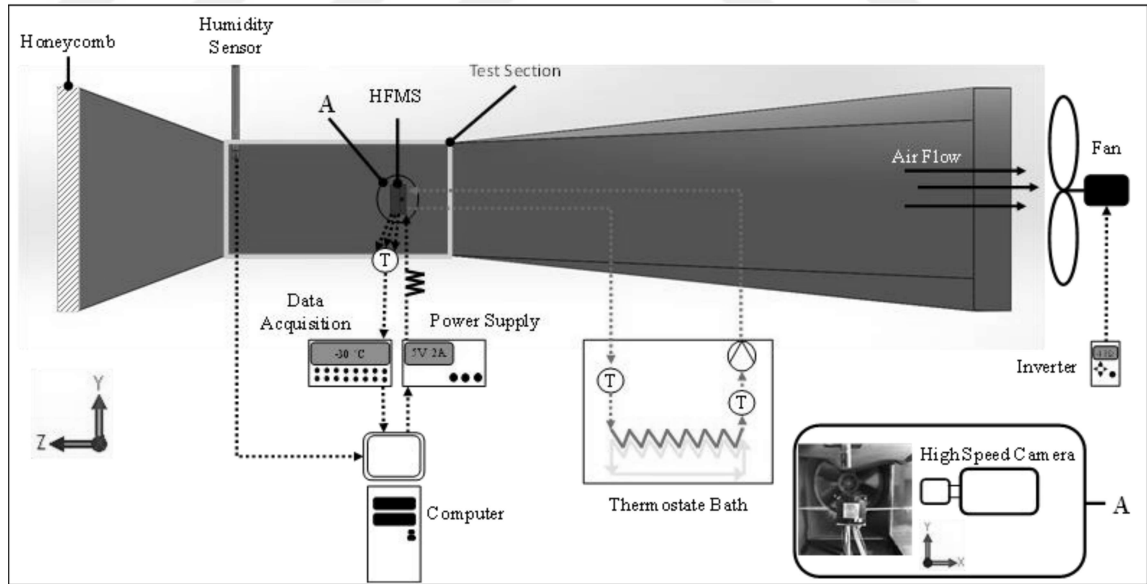


Figure 8. Schematic of the test system.

The maximum Re number was calculated as 410000 for 20°C air temperature, which corresponds to the velocity of 20.6 m/s. The Reynolds number is important for velocity comparisons between studies. In this study 30000 (1.5m/s), 40000 (2 m/s),

50000 (2.5 m/s) and 60000 (3 m/s) Re numbers have been used to investigate air velocity effects on frosting. A humidity sensor was placed at the entrance of the test section. The size of the test section is 300x300 mm². A plexiglass plate (300x600 mm²) was mounted at the side of the test section to observe frost propagation on the surfaces. The Heat Flux Measurement System (HFMS) was placed inside the test section for the vertical and horizontal alignment experiments. A hole (40x40 mm²) was drilled at the top of the test for the parallel orientation of the surfaces, as shown in Figure 9.

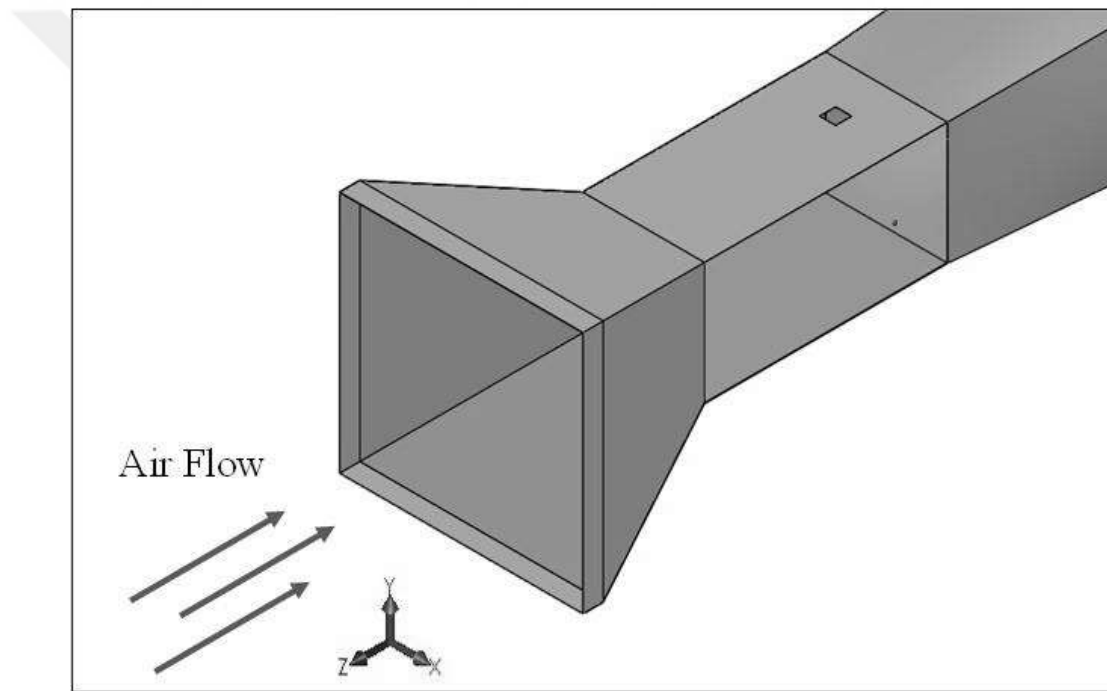


Figure 9. Access window at the tunnel.

The HFMS has been designed to investigate the effects of different air velocities, temperature, humidity and surface properties on the heat flow rate, and frost thickness under frosting conditions. The system involves a cold plate, two thermoelectric devices (TEC1-12715), three aluminium plates and two aluminium glasses. Different surfaces can be mounted on top of the HFMS. The cold plate was designed to cool down the thermoelectric devices. Methylene glycol-water mixture

(40%) was circulated in the cold plate by a chiller. The chiller was kept at -5°C . Two DC power supplies were used to provide electrical power to the thermoelectric devices. All of the plates are square in shape with a side length of 4 cm. The aluminium plates are 3 mm while the glass plates are 2 mm in thickness. Two glass plates were attached to the top of the aluminium plates to increase the thermal resistance of the HFMS. Aluminium plates were used to provide uniform heat flux between the layers.

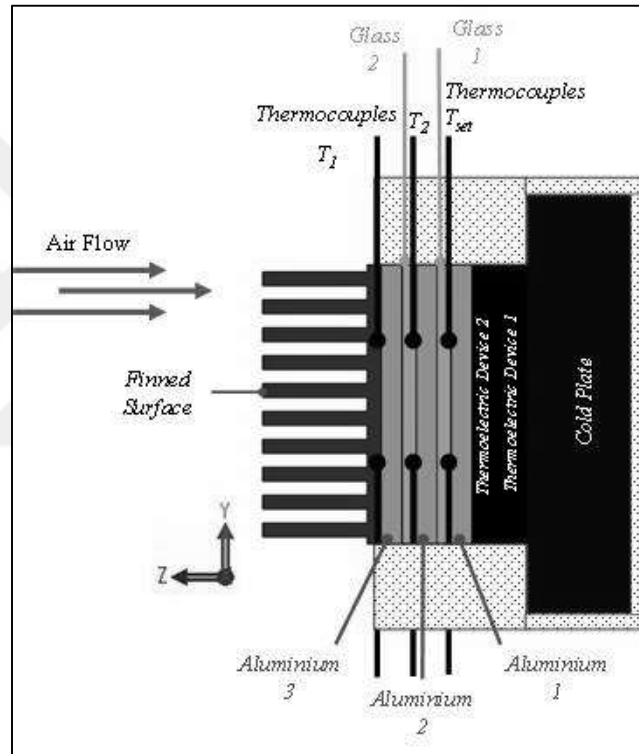


Figure 10. Cross-section of HFMS.

Figure 10 shows the construction of the HFMS. Four T-type thermocouples (12 in total) were placed on each aluminium plate. Different surface TCs were mounted on top of the HFMS. A thermal compound was used between plates to decrease contact resistance between the layers. An isolation material (ABS) for the round of the HFMS was produced by a 3D printing machine. One-dimensional heat conduction has been assumed from outer surface to the cold plate.

3.2 Preparation of Samples for Frost Formation

HFMS was designed as a modular system to replace different surfaces. In this study, different finned and unfinned surfaces have been investigated under frosting conditions.

3.2.1 Unfinned Surface

Aluminium metal was used to produce unfinned surfaces. The size of each plate was 0.04x0.04 m. A CNC milling machine was used to produce these surfaces. Unfinned surfaces were utilized to develop basic density prediction model.

3.2.2 Finned Surfaces

Different finned surfaces, which are inline, staggered and knife-edge, were produced to investigate the effect of geometrical properties of finned surfaces on frost formation. Different fin lengths have been chosen for inline fins. 6 different fin lengths between 5 and 30 mm were used. Finned surfaces with 5 mm, 10 mm and 15 mm lengths were produced by a CNC milling machine. A cold saw was used to manufacture the finned surfaces above 20 mm. All of these finned surfaces have 2 mm fin spacing.

Fin spacing effect of inline fin types on frost propagation was investigated with different fin gaps varied by 1 mm from 2 to 6 mm. 15 mm fin length has been chosen for the length of these finned surfaces. The projected surface area in the air flow direction was 40 x 40 mm. A hole (0.7 mm in diameter) was drilled to measure the temperature of the fin tips for only inline fins. The distance between the fin tip and the center of the hole was set to 0.85 mm (see Figure 11). Staggered and knife edge fin types were produced at two different fin lengths (5 mm and 15 mm). Details of the fins are shown in Figure A-1, 2 and 3.

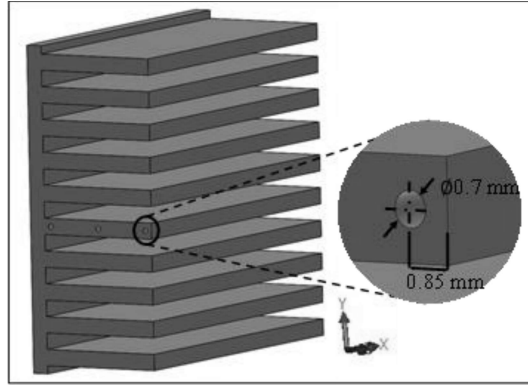


Figure 11. Temperature measurements point at the fin tip.

3.2.3 Coated Surface

Finned and unfinned surfaces with a fin length of 15 mm and fin gap of 2 mm was coated by a superhydrophobic coating liquid. A study by Salem et al [44] was used to determine the coating method of surfaces. The dip-coating method was chosen to obtain superhydrophobic finned and unfinned surfaces. Bottom and top coating liquids of the ultra-ever company were used for coating. The liquid of the bottom coating has been stirred for 5 minutes. The surface was dipped in liquid for five minutes. The samples were then allowed to dry for 1 hour. This process was repeated two times. A top coating liquid has been applied with the same method as coated surface. The drying time of top coated surfaces was 24 hours. Surfaces were dipped in liquids with 50 mm/min immersion velocity. Droplet contact angles of finned and unfinned surfaces were measured as larger than 150° after the coating.

3.3 Measurement Techniques

Two heaters and a humidifier have been used to obtain stable air temperature and relative humidity in the laboratory. The humidity sensor located at the entrance of the test section measures the air temperature and relative humidity of the air inside the

tunnel. Measured air velocity and relative humidity were recorded on a computer by the software of the sensor. Temperature of the top of the thermoelectric devices has been settled/adjusted or controlled by the PID control program (LabView). T-type thermocouples measurements were monitored by LabView. Temperatures of fin tips were only measured for the vertical and horizontal orientation of inline fin types. Phantom V311 high-speed camera was used to take pictures of the frost formation process. The camera was positioned/place outside the tunnel, as can be seen in Figure 8. Averages of T_1 and T_3 temperatures were used to calculate the heat flow rate of HFMS.

Eq 1 shows the thermal resistance R_{cond} between T_1 and T_3 .

$$R_{cond} = 2 \left(\frac{t_{glass}}{k_{glass}A} + \frac{t_{Al}}{k_{Al}A} \right) \quad (1)$$

Under steady-state conditions, the heat flow rate through the device can be calculated by using Eq 2.

$$\dot{Q}_{fin} = \frac{\Delta T}{R_{cond}} \quad (2)$$

The equipment list and properties of the experimental setup are provided in Table 1.

Table 1. Model and properties of the experimental equipment.

Equipments	Technical Properties	
Agilent Data Acquisition	$\pm 1.0\text{ }^{\circ}\text{C}$	
Agilent Power Supply	25 V	7 A
TEC1-12715	136 W Max. Cooling Power	70 $^{\circ}\text{C}$ Max. Temperature Difference
Huber Ministat 125 Chiller	-25 / 150 $^{\circ}\text{C}$	0.3 kW Max. Cooling Power
S&P Suction Fan	6925 m ³ /h	225 Pa Total Pressure
Omega Humidity Sensore	$\pm 3\%$ Relative Humidity Accurate	$\pm 1\%$ Temperature Accurate
Omega T-Type Thermocouples	$\pm 0.5\text{ }^{\circ}\text{C}$ Temperature Accurate	

3.4 Design of Experiments

Experiments were designed to investigate the effect of different parameters on heat flow rate, temperature, and frost thickness for frosting conditions. Before taking the measurements, the surface was brought to thermal equilibrium with the surrounding air. The fluctuations in air temperature and relative humidity were around 1-3%. These values are within the uncertainty range of the humidity sensor. In all of the experiments,

the air temperature was kept at 18°C. The parameters of the conducted experiments are given in Table 2. Orientations of surfaces during testing are shown in Figure 12.

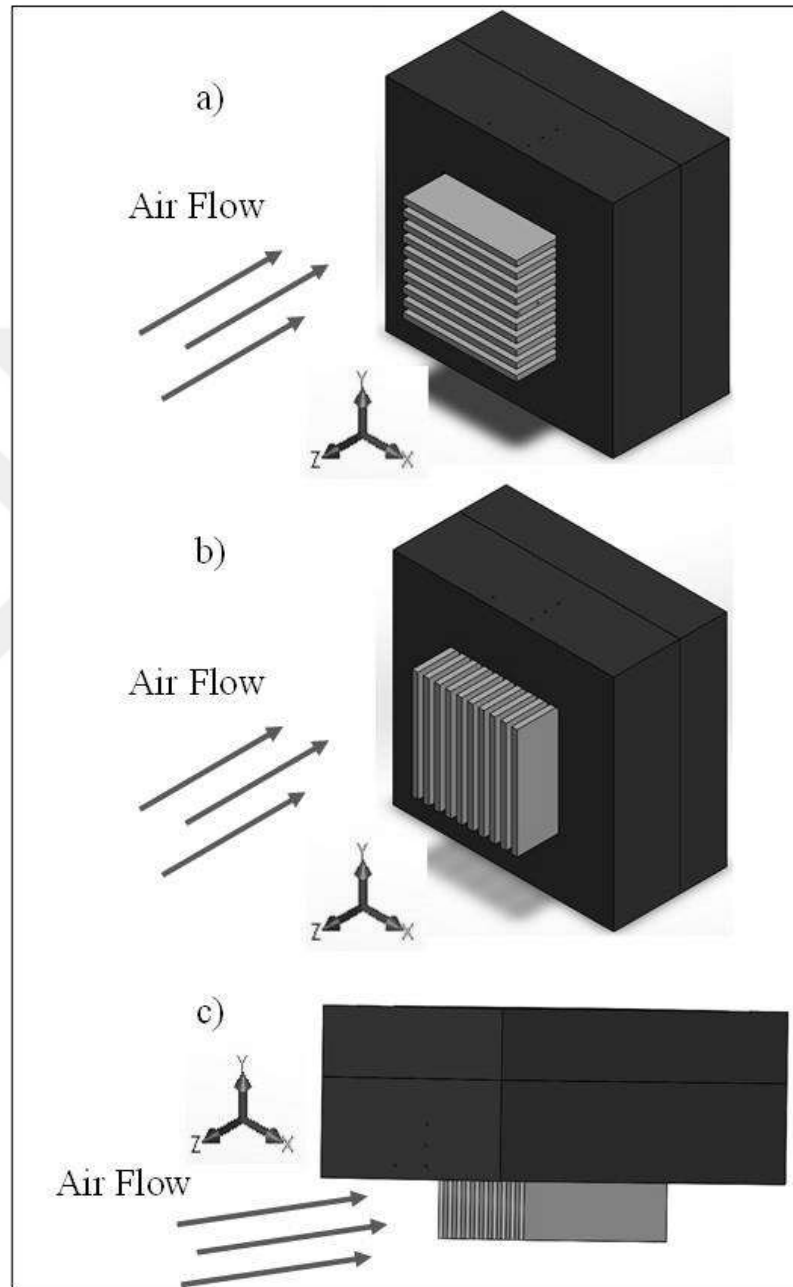


Figure 12. Alignments of surfaces (a) Horizontal orientation (b) Vertical orientation and (c) Parallel orientation.

Table 2. Measurement codes and process parameters of experiments.

Code	L [mm]	S [mm]	T _{set} [°C]	T _{air} [°C]	V _{air} [m/s]	RH [%]	Vertical/ Horizontal/Parallel	Coated/ Uncoated	Fin Types	AoA [°]
RH1	15	2	-20	18	1.5	40	H	U	Inline	90
						55				
RH2	15	2	-30	18	1.5	40	H	U	Inline	90
						55				
						65				
V1	15	2	-30	18	1.5	55	V	U	Inline	90
					2					
					2.5					
V2	15	2	-30	18	1.5	55	H	U	Inline	90
					2					
					2.5					
V3	15	2	-30	18	3	55	V	C	Inline	90
					1.5					
					2					
S1	15	2	-30	18	1.5	55	H	U	Inline	90
		3								
		4								
		5								
		6								
S2	15	0	-30	18	1.5	55	P	U	Inline	0
		2								
		5								
		6								
L1	5	2	-20	18	1.5	40	H	U	Inline	90
	10									
	15									
	20									
	25									
	30									
L2	5	2	-30	18	1.5	40	H	U	Inline	90
	10									
	15									
	20									
	25									
	30									
L3	5	2	-30	18	2	55	P	U	Inline	0
	15									
FT1	15	6	-30	18	1.5	55	P	U	Inline/S/KE	0
FT2	15	6	-30	18	2	55	P	U	Inline/S/KE	0
FT3	15	6	-30	18	1.5	55	H	U	Inline/S/KE	90
C1	15	2	-30	18	1.5	55	V	C/U	Inline	X
C2	15	2	-30	18	2	55	V	C/U	Inline	X
C3	15	2	-30	18	1.5	55	P	C/U	Inline	X
A1	15	2	-30	18	1.5	55	V/H/P	U	Inline	X

3.5 Uncertainty Analysis

The uncertainty in the heat transfer rate $\dot{Q}_{fin}$ was calculated with the Gaussian uncertainty method [45] as shown in Eq (3), Eq (4) and Eq (5). The uncertainty in the temperature measurements is taken as $\pm 0.5^\circ\text{C}$ and the uncertainty in the plate thickness is considered as $\pm 5 \mu\text{m}$.

$$\frac{\omega_{\dot{Q}_{fin}}}{\dot{Q}_{fin}} = \left[\left(\frac{\partial \dot{Q}_{fin}}{\partial A} \cdot \frac{\omega_A}{\dot{Q}_{fin}} \right)^2 + \left(\frac{\partial \dot{Q}_{fin}}{\partial \Delta T} \cdot \frac{\omega_{\Delta T}}{\dot{Q}_{fin}} \right)^2 \right]^{1/2} \quad (3)$$

$$\frac{\omega_{\dot{Q}_{fin}}}{\dot{Q}_{fin}} = \left[\left(k \cdot \Delta T \cdot \frac{\omega_A}{k \cdot \Delta T \cdot A} \right)^2 + \left(k \cdot A \cdot \frac{\omega_{\Delta T}}{k \cdot \Delta T \cdot A} \right)^2 \right]^{1/2} \quad (4)$$

$$\frac{\omega_{\dot{Q}_{fin}}}{\dot{Q}_{fin}} = \left[\left(\frac{\omega_A}{A} \right)^2 + \left(\frac{\omega_{\Delta T}}{\Delta T} \right)^2 \right]^{1/2} \quad (5)$$

$$\frac{\omega_{\epsilon}}{\epsilon} = \left[\left(\frac{\partial \epsilon}{\partial \dot{Q}_{fin}} \cdot \frac{\omega_{\dot{Q}_{fin}}}{\epsilon} \right)^2 + \left(\frac{\partial \epsilon}{\partial \dot{Q}_{unfin}} \cdot \frac{\omega_{\dot{Q}_{unfin}}}{\epsilon} \right)^2 \right]^{1/2} \quad (6)$$

For all the cases, the average time-dependent thickness of the developed frost was measured by using the images taken with the camera. All frost thickness measurements were carried out along the z -axis, while the initial thickness value was taken when all the fin tips and edges were covered with frost. The calculation of instantaneous frost thickness was done by detecting the pixel-wise propagation of the air-frost interface multiplied by the resolution of the high-speed camera. The uncertainty of thickness measurements was found to be $\pm 50 \mu\text{m}$. Heat transfer rate and fin effectiveness uncertainties was shown in Figure A-4.

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 Effect of Relative Humidity

Air relative humidity and surface temperature have dominant effects on the accumulated frost thickness. In this part, the effect of the relative humidity (RH) on the accumulated frost thickness and heat transfer rate has been investigated for two different surface temperatures. 40, 55 and 65% RH levels have been chosen for the experiments. A more detailed description of the experimental conditions is listed in Table 3.

Table 3. Experimental conditions for the experimental campaigns RH1 and RH2

Code	L [mm]	s [mm]	T _{set} [°C]	T _{air} [°C]	Air Velocity [m/s]	RH [%]	Vertical/ Horizontal/Parallel	Coated/Uncoated	Fin Types	AoA [°]
RH1	15	2	-20	18	1.5	40	H	U	Inline	90
			55							
RH2			-30			40				
						55				
						65				

The length of fins (L) is set to 15 mm while the fin space (s) is set to 2 mm based on the previous experimental findings. Two different set temperatures for the surfaces were used. In all the experiments the air temperature was kept constant at T_{air} = 18 °C. The fins are oriented horizontally as shown in Figure 13.

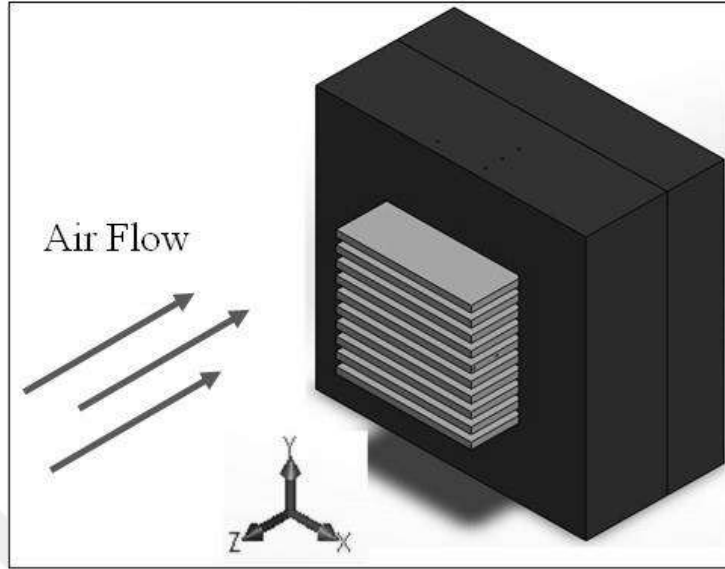


Figure 13. Orientation of relative humidity experiments surface.

4.1.1 RH1 Experiments

Figure 14a-b shows the variation in the heat flow rate in time. The results show a sudden drop in the heat flow rate with the onset of the frost accumulation on finned surfaces. Before that instant, a slight drop in the heat flow rate was observed. This reduction is thought to be due to the accumulation of the condensing water droplets on the finned surfaces and thereby reducing the effective surface area. The accumulated water droplets are observed to be bigger in size when the relative humidity level is higher. Moreover, the time it required for the onset of the frosting is heavily increased with the increase in the relative humidity level. With the relative humidity level of 55% the initial frost accumulation was observed after about 250 min. However, with the 40% humidity level the initial frost accumulation was observed much earlier, about 90 min after the start of the experiment. It is also worth to express that a spike in the fin tip temperature was observed at the initiation of the frosting process. (Figure 15) The rise in the temperature during the frosting process was mentioned in the literature too [43]. This behaviour was very subtle with the low relative humidity conditions but very

pronounced when the relative humidity was high. At a relative humidity of 55% a spike in the heat flow rate was observed. This sudden increase in the heat flow rate is due to the release of the latent heat during the solidification of the water droplets. It might be that a higher mass of condensed water droplets on finned surfaces at higher humidity levels leads to a more pronounced spike in the heat flow rate during the frosting. Figure 15 shows the temperature of the fin tip. As shown, in both relative humidity levels the temperature at the fin tip was measured below 0 °C even before the frosting took place. When the frosting starts the tip temperature rises and then starts to drop gradually again. The rise in the tip temperature happens much later with the high relative humidity case.

The frost thicknesses for 40% and 55% relative humidity levels can be seen in Figure 16. In this figure the frost thickness is given as the average frost thickness on all fin edges. The increases in the frost thicknesses with time are comparable in both experiments conducted with 40% and 55% relative humidity levels. However, one can also see a more pronounced frost formation towards the root of the fin with the higher relative humidity level.

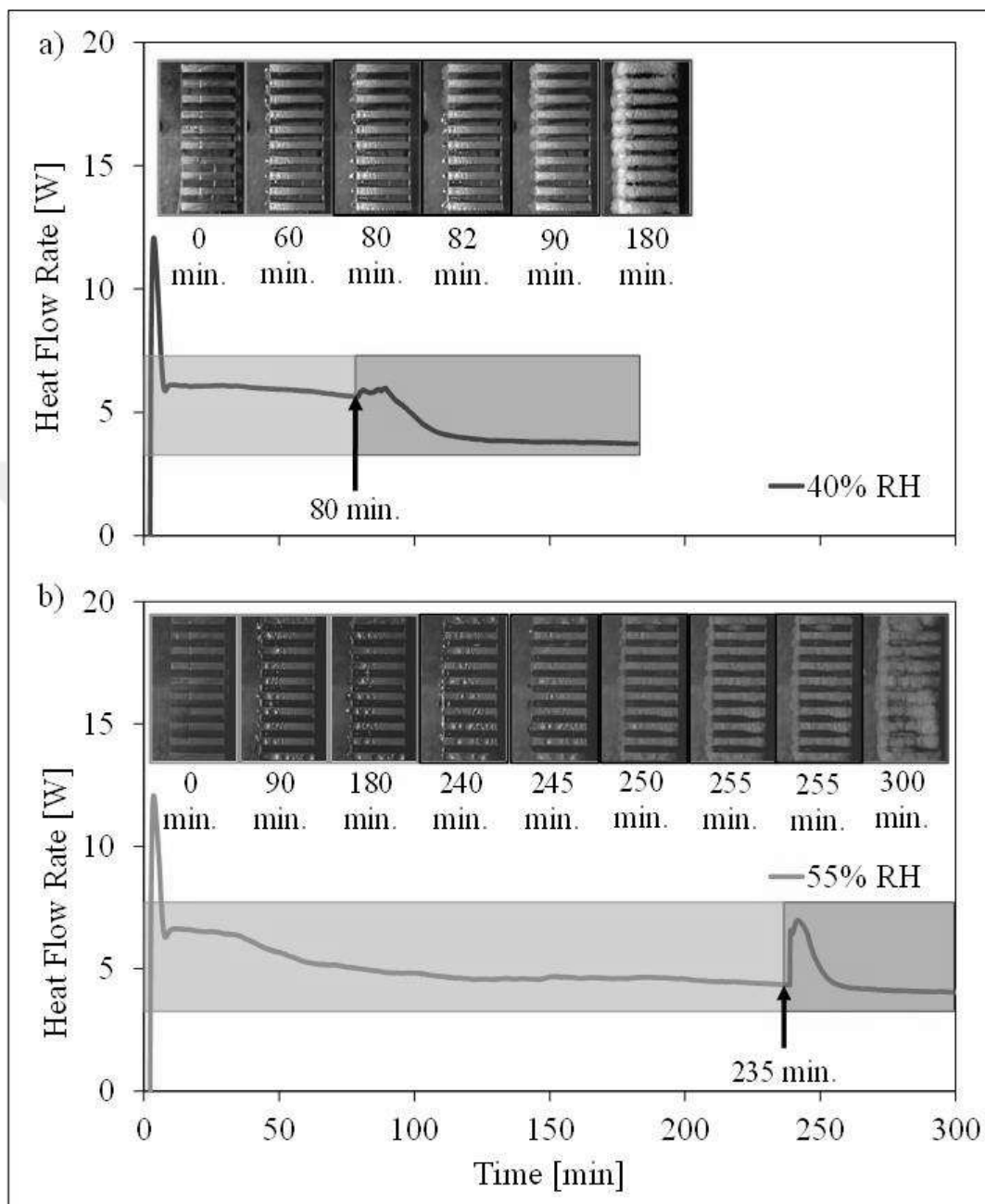


Figure 14. Heat flow rate variations of (a) 40% RH and (b) 55% RH conditions for RH1 experiments.

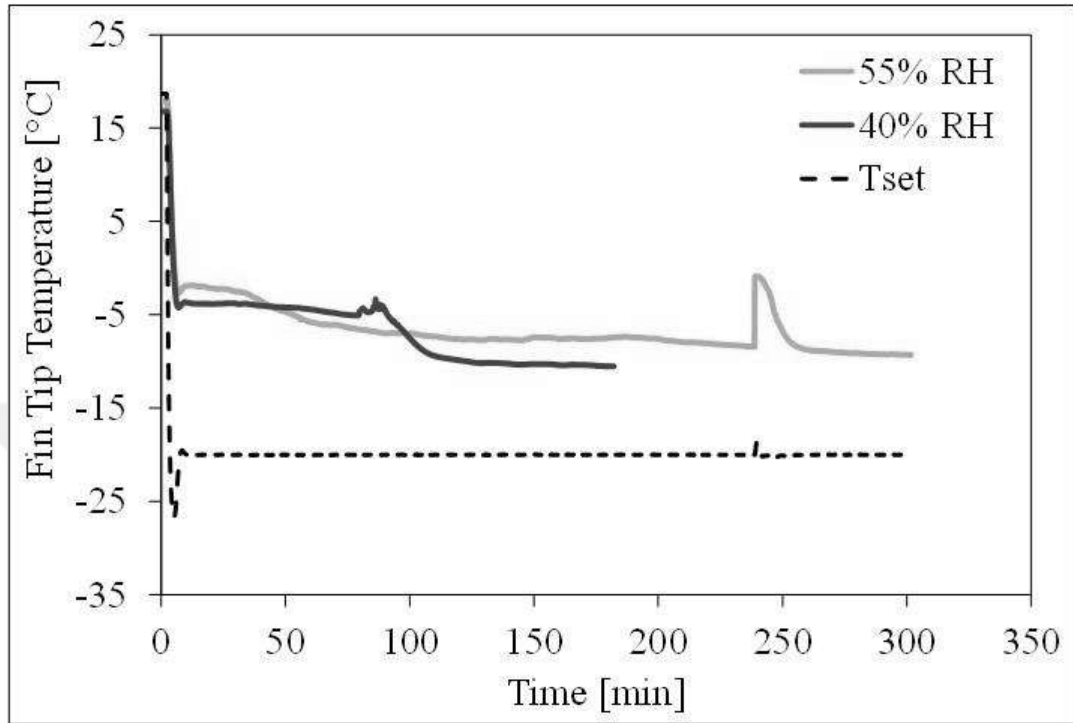


Figure 15. Temperature variations of RH1 experiments.

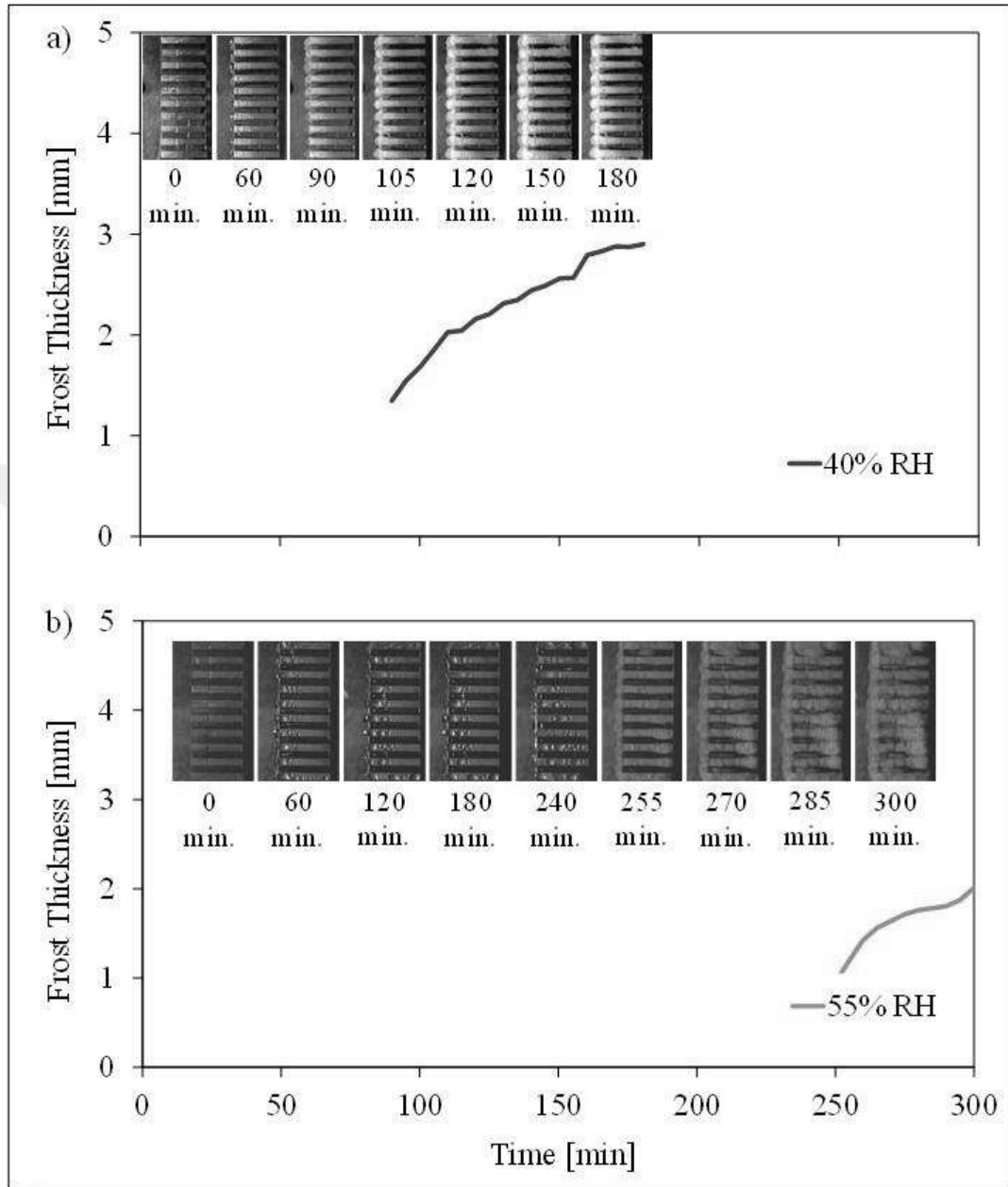


Figure 16. Frost thickness measurements of RH1 experiments for a) 40%RH and
b) 55% RH.

4.1.2 RH2 Experiments

In this experimental study, the effect of the relative humidity on frosting were investigated at a lower base temperature than in the previous experimental study. The base temperature of the finned surface was set to -30°C . Figure 17 shows the heat flow

rate through the finned surface with respect to time. In all of the three relative humidity levels a sudden drop in the heat flow rate was observed with the initiation of the frosting. This again is associated with the blockage of the tips of the finned surfaces with the frost accumulation. The drop in the heat flow rate in the relative humidity levels 40% and 55% are very similar to each other where the frosting starts at about 15 min later than the experiments start. However, with the relative humidity level of 65 % the drop in the heat flow rate is observed at about 35 min after the start of the experiment. The delay in the drop in the heat flow rate with the increase in the relative humidity level is consistent with the findings of the previous measurements discussed in the previous chapter. It is also worth to mention, that at 65% relative humidity level the drop in the heat flow rate is more sudden and spikier compared to the drop in the lower relative humidity levels. Figure 18 shows the fin tip temperature for all three humidity levels. Observations in the fin tip temperature are very similar to the findings in Figure 15. After the frosting took place the fin tip temperatures do vary only slightly between different relative humidity levels. Figure 19 shows the average frost thickness on the fin tips. As shown, higher relative humidity results in a higher frost thickness at the finned tip. However, one can also observe a more pronounced frost accumulation of the fin roots with the higher relative humidity levels.

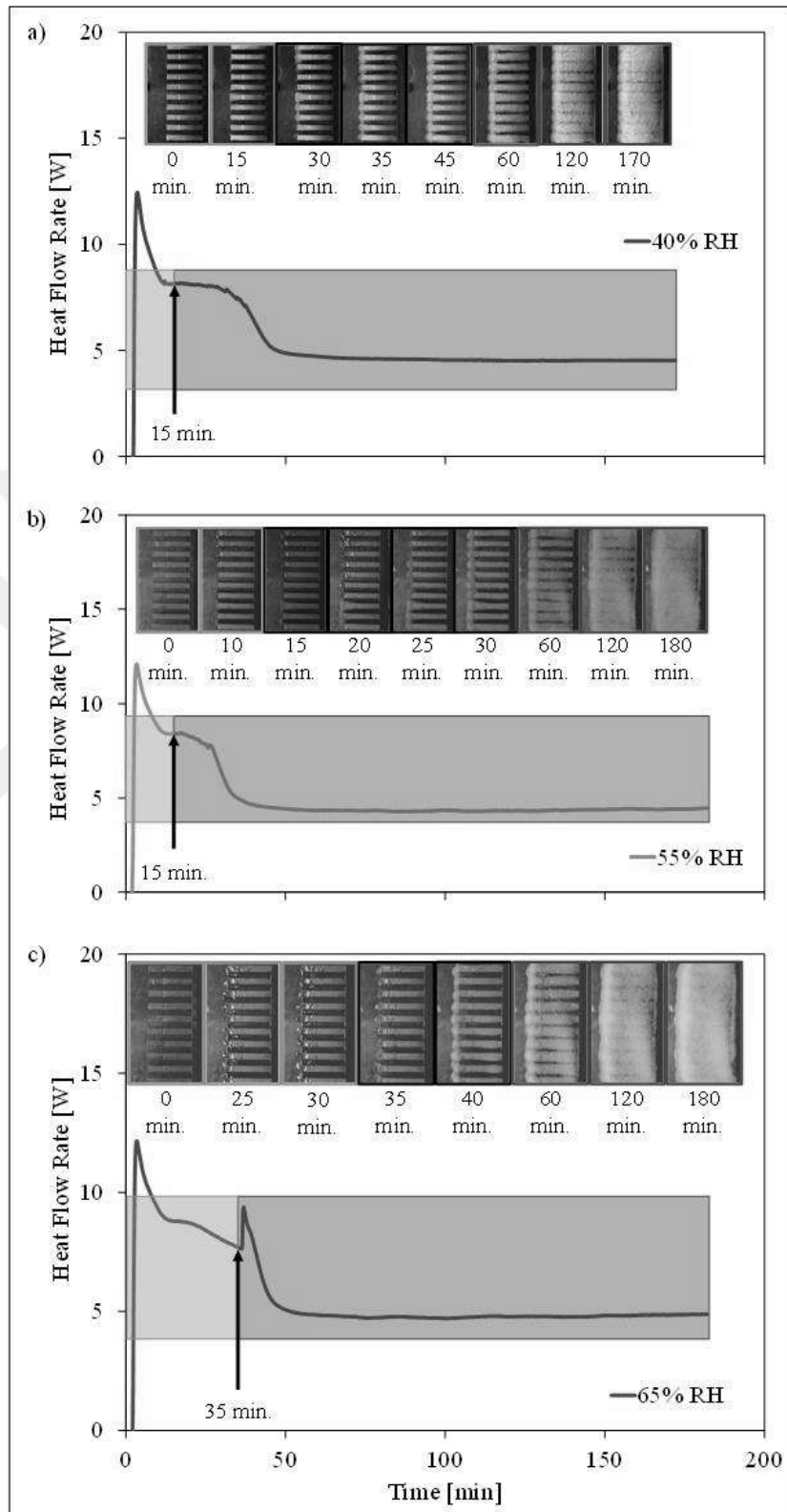


Figure 17. Heat flow rate variations of a) 40% RH b) 55% RH and c) 65% RH conditions for RH2 experiments.

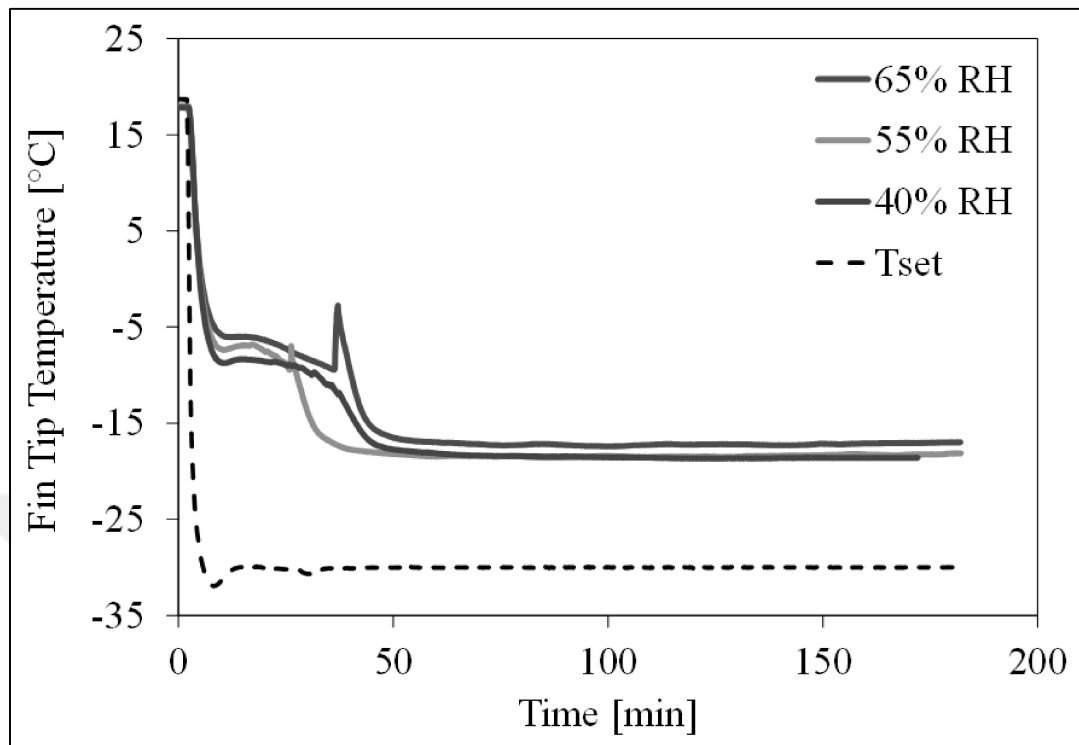


Figure 18. Behaviours of fin tip temperature at different relative humidity for the set temperature of -30°C .

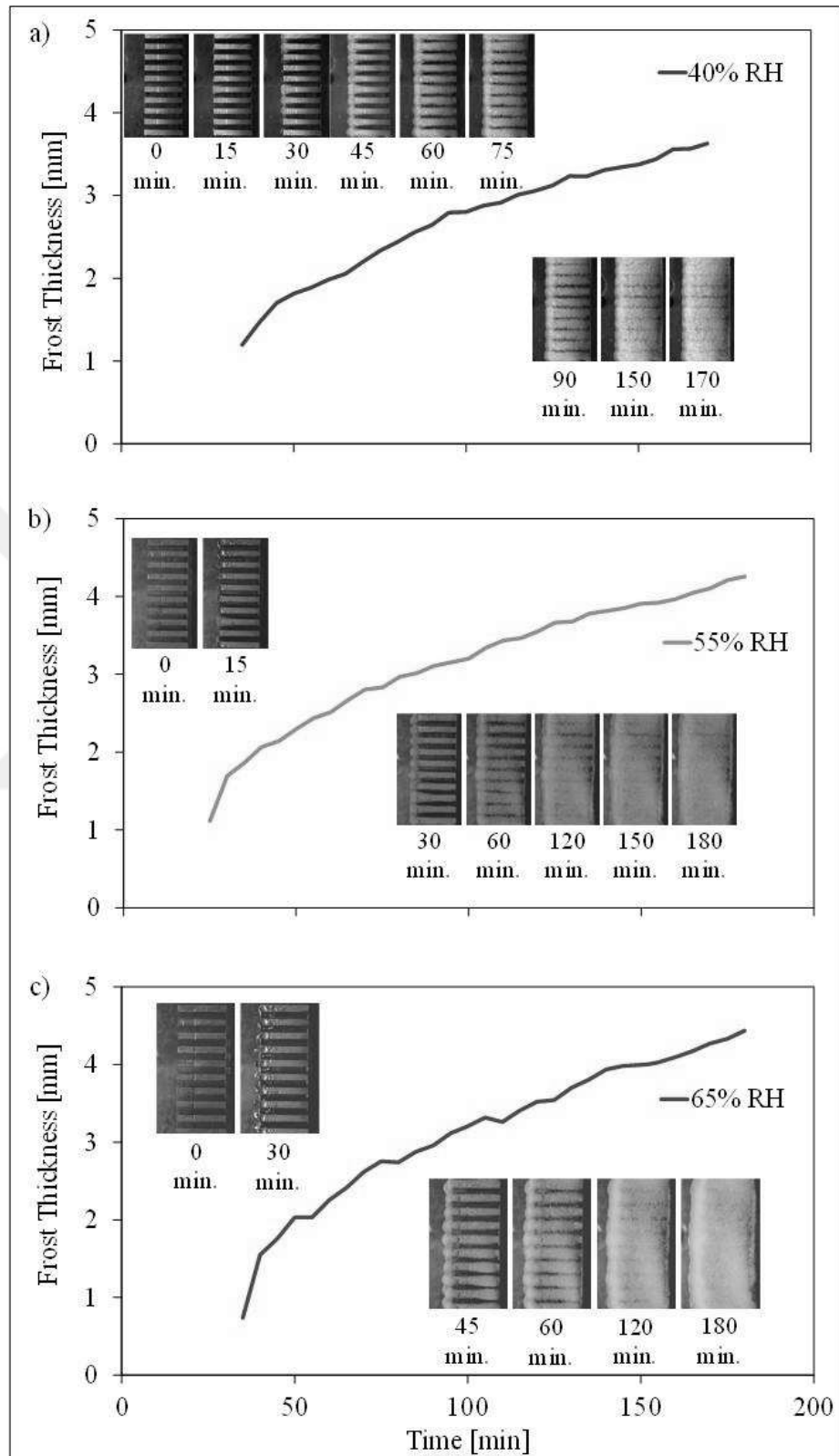


Figure 19. Frost thickness measurements of RH2 experiments for a) 40%RH
b) 55% RH and c) 65% RH.

4.2 Effect of Air Velocity

In this section the effect of the air velocity on frost formation was investigated for different orientations of the finned surface and with and without coating. Table 4 shows the test conditions for the conducted experiments. Since at high air velocities the frost accumulation on the surface is suppressed the air velocity was increased only up to 3 m/s.

Table 4. Selected parameters in the air velocity effect experiments.

Code	L [mm]	s [mm]	T _{set} [°C]	T _{air} [°C]	Air Velocity [m/s]	RH [%]	Vertical/ Horizontal/Parallel	Coated/Uncoated	Fin Types	AoA [°]
V1	15	2	-30	18	1.5	55	V	U	Inline	90
					2					
					2.5					
					1.5					
V2					2		H			
					2.5					
					3					
					1.5		V	C		
V3					2					
					2.5					

For V1, V2 and V3 finned surface tests only that are 15 mm in length and with a fin spacing of 2mm were used. In these experimental measurements, the base plate temperature T_{set} was set to -30°C and the air temperature was kept at 18°C . Inline fins were positioned horizontal and vertical for the test conditions. The orientations of the finned surfaces are shown in Figure 20.

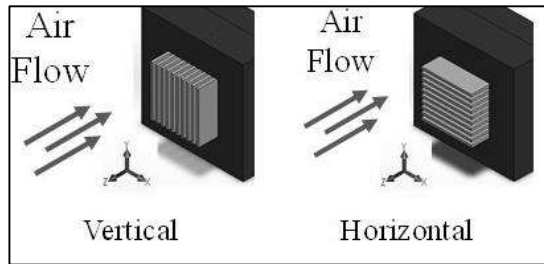


Figure 20. Orientations of different air velocity investigation experiments a) Vertical and b) Horizontal.

4.2.1 V1 Experiments

In the experiment V1, the finned surfaces were held vertically and no coating was applied onto the surfaces. Figure 22 shows the heat flow rate through the surface for three different air velocities. In all the experiments conducted at different air velocity conditions the heat flow rate shows a sudden drop caused by the freezing of the condensed water droplets on the finned surface. The frost accumulation on the finned surface blocks the air penetration between the fins and thereby the effectiveness of the finned surface is heavily reduced. This behaviour was observed at all velocity levels. However, the drop in the heat flow rate is observed at different instants in time at different air velocity levels. The higher the air velocity the more the drop in the heat flow rate is delayed. Moreover, a slight peak in the heat flow rate was also observed during the initiation of the frosting process. However, this behaviour is more pronounced at air velocity levels above 2 m/s. This could be due to the difference in the accumulated condensed water mass on the finned surface. Comparing the heat flow rates after the frosting had taken place one can see that the higher the air velocity the higher is the heat flow rate.

Fin tip temperatures are shown in Figure 22. Similar to the behavior in the heat flow rate, a sudden drop in the fin tip temperatures were observed with the onset of the frosting at the fin tip. The final fin tip temperatures do slightly vary with the incoming air speed. The higher the air velocity the higher is the fin tip temperature. Figure 23 shows the accumulated average frost thickness on the fin tips. The higher the air velocity the more is the initial frost accumulation is delayed. However, the rate of increase in the frost thickness on the fin tip is comparable in all velocity levels.

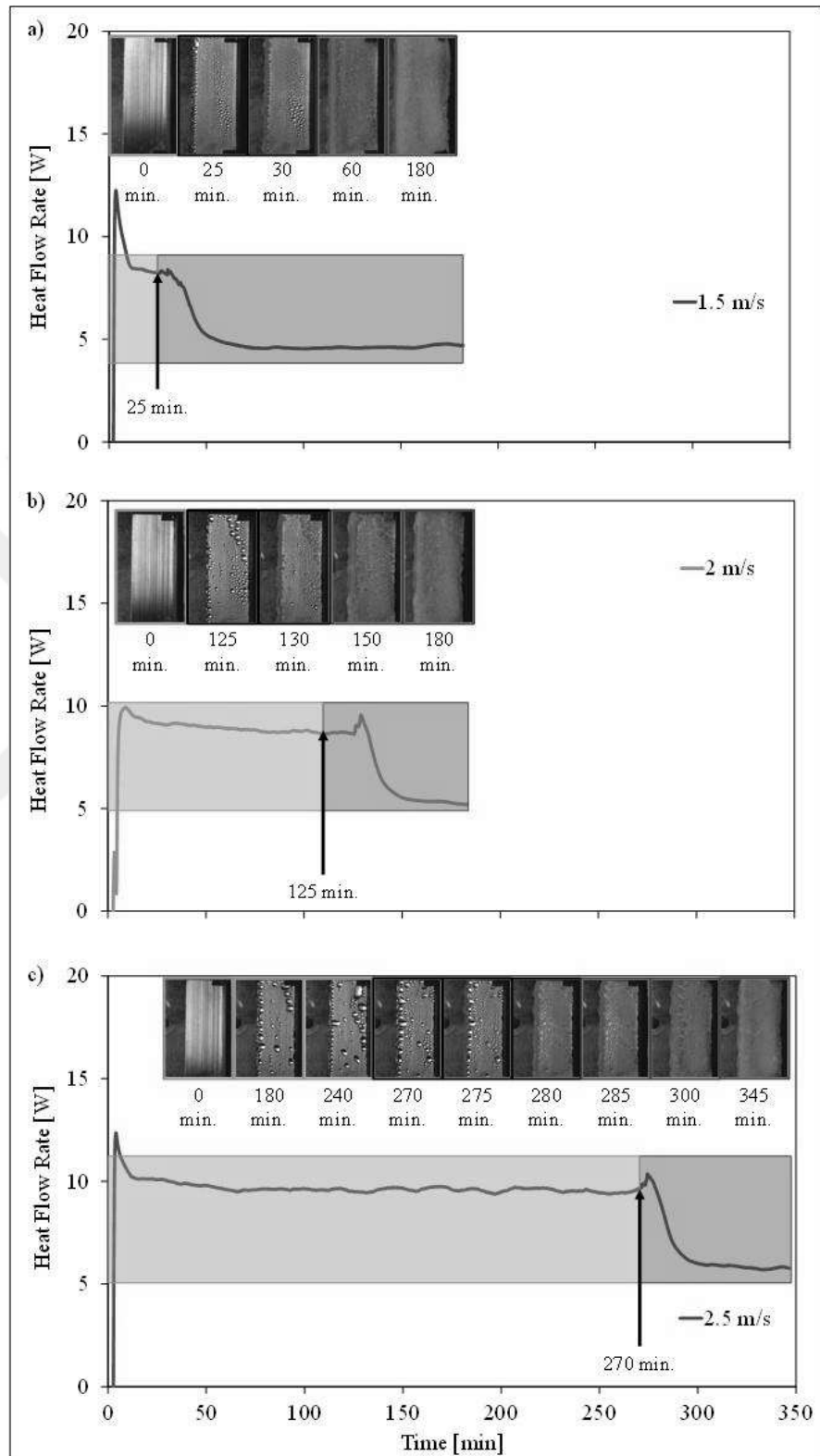


Figure 21. Heat flow rate variations of a) 1.5 m/s b) 2 m/s and c) 2.5 m/s test conditions for V1.

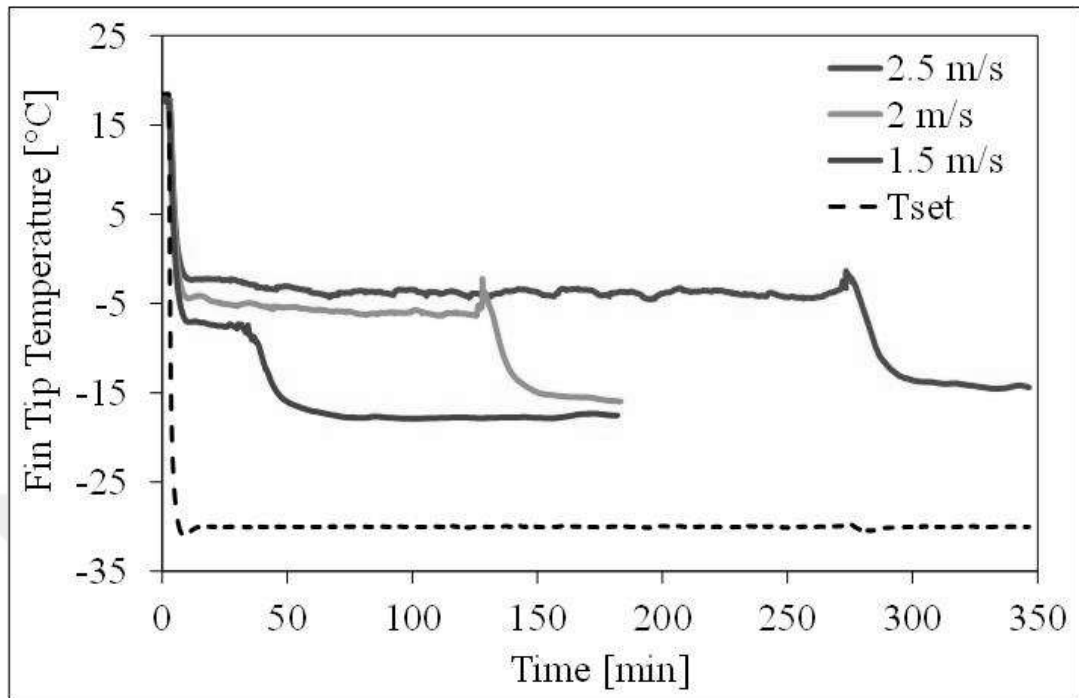


Figure 22. Effect of fin tip temperature for the set temperature of -30°C and vertical configuration of fins in experiment V1.

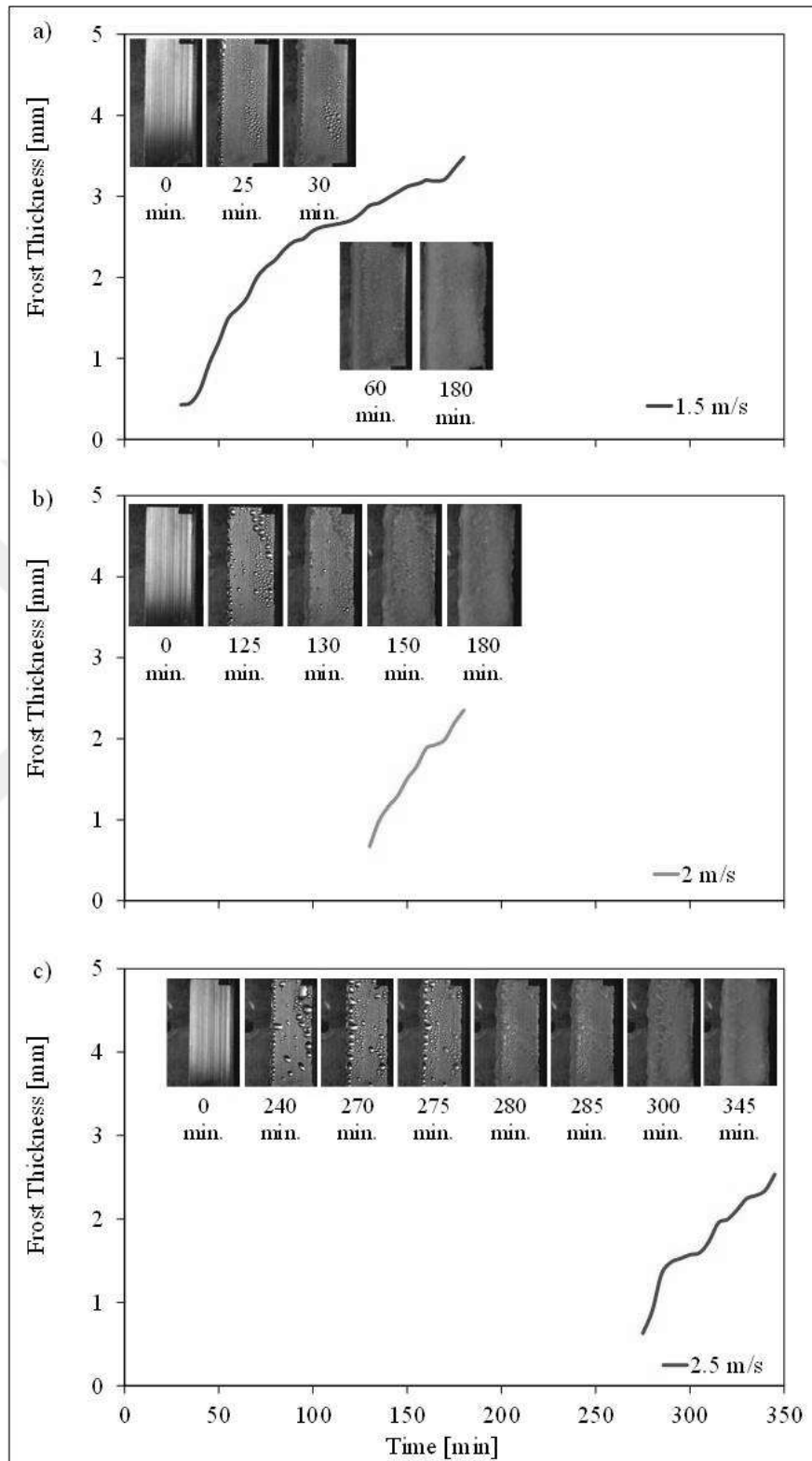


Figure 23. Frost thickness measurements for V1 a) 1.5 m/s air velocity b) 2 m/s air velocity and c) 2.5 m/s.

4.2.2 V2 Experiments

In these set of experiments the finned surface was positioned horizontally and the same measurements as in V1 were conducted. Figure 24 and Figure 25 show the heat flow rate into the surface during the experiments. Similar to the findings in V1 higher air velocity also results in further delay in the initial frost build-up which is characterized by the sudden drop in the heat flow rate. After complete frost coverage the heat flow rate into the finned surface is also found to be higher at higher air velocities. This result has also been reported by Hernandez et al. [23]. In Figure 26, the fin tip temperatures and the average frost thickness on the fin edges were shown. Fin tip temperatures measured after the complete frost coverage were found to be higher at higher air velocities. This finding is consistent with the increase in the heat flow rate with increasing air speeds. In Figure 26b, the average frost thicknesses on the fin tips were shown. The initial frost build-up was delayed with the increase in the air velocity. However, the rate of increase in the frost thickness at different air velocities were similar at different air velocity levels. Previous studies from literature [8,13] indicate that the air velocity does not have any influence on the frost thickness. Similarly, Shen and Wang [32] presented in their study that air velocity had a very small effect on frost thickness. In the current study, the variations in the accumulated frost thickness are due to the differences in the formation of the initial frost build-up. However, once the initial frost is accumulated the rate of increase in the frost thickness was very similar between different air velocities.

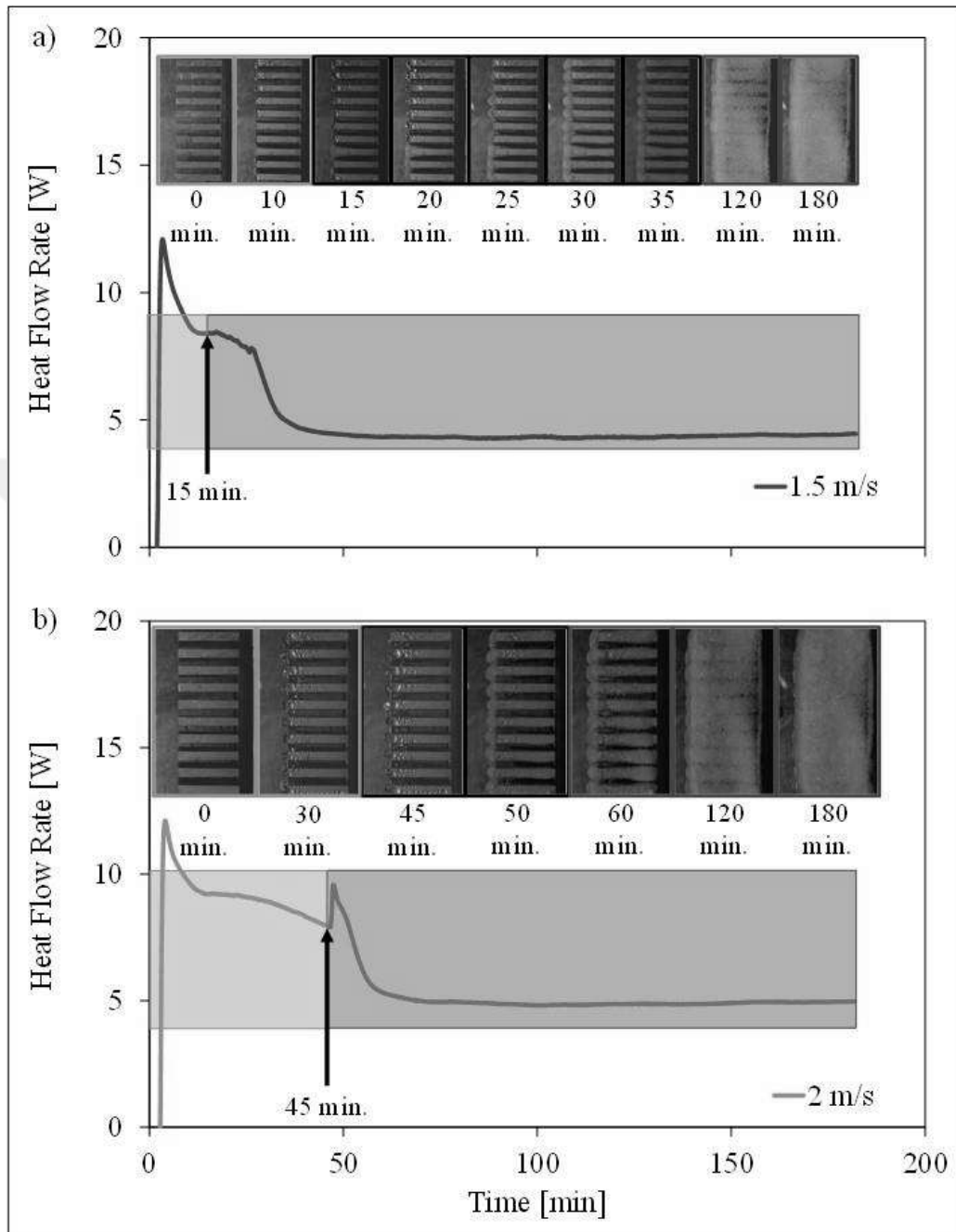


Figure 24. Heat flow rate variations of a) 1.5 m/s and b) 2 m/s test conditions for V2.

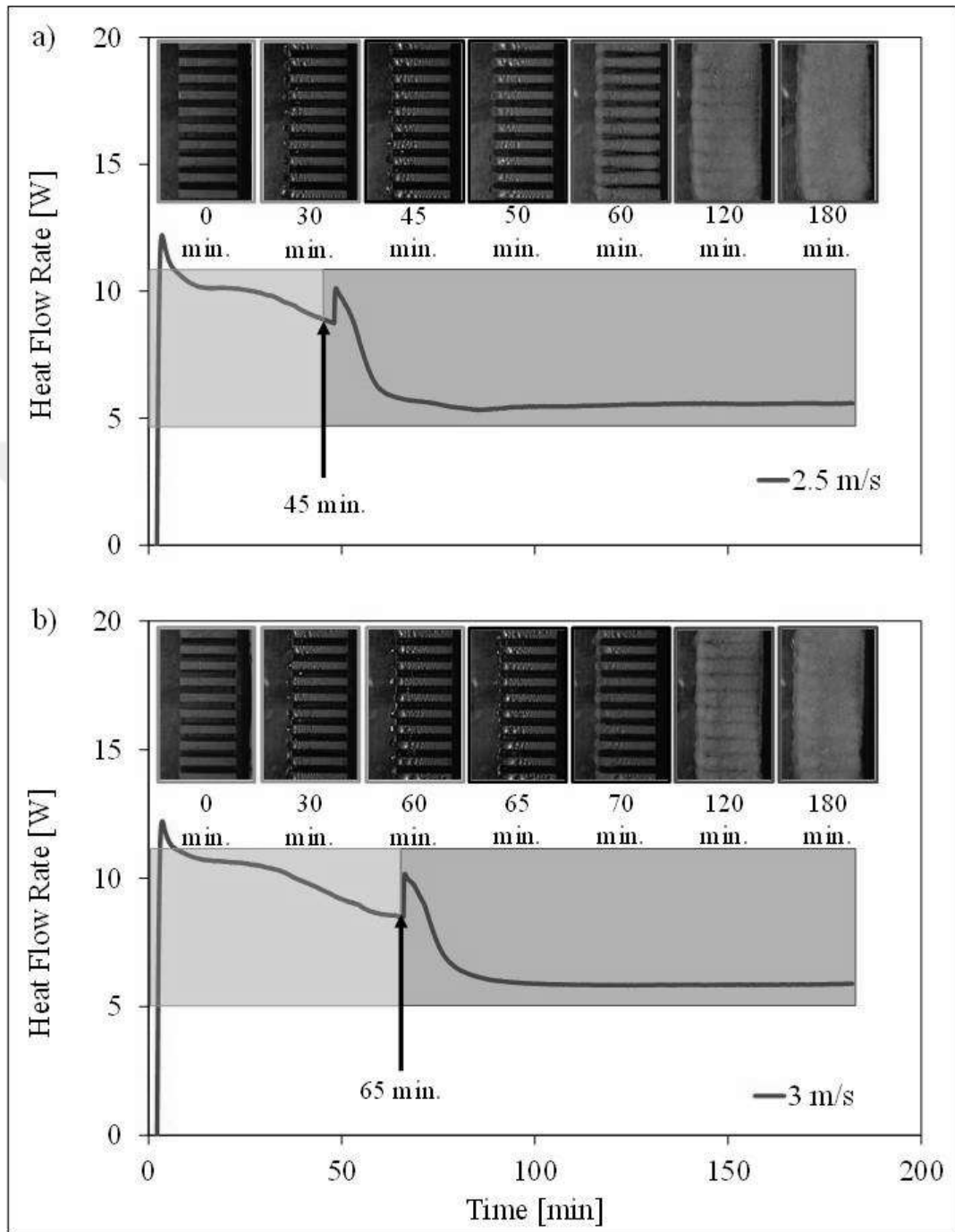


Figure 25. Heat flow rate variations of a) 2.5 m/s and b) 3 m/s test conditions for V2.

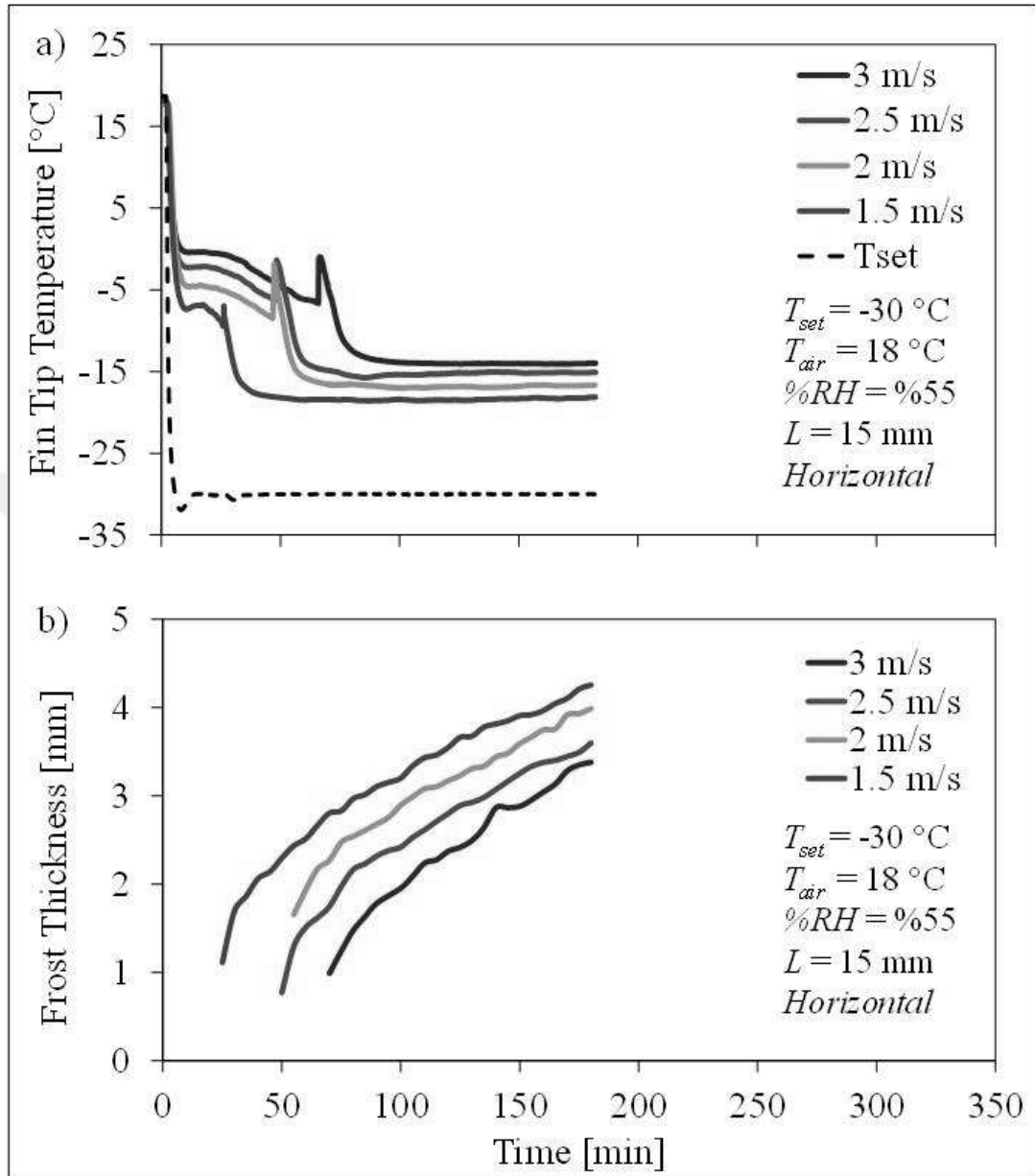


Figure 26. Different air velocity effects on the finned surface in the experiment V2

a) Fin tip temperature and b) Frost thickness.

4.2.3 V3 Experiments

In these set of experiments, the experimental conditions in V1 were realized again however, this time the surfaces were coated. Figure 27 also shows the heat flow rate into the finned surface at different air velocity levels. At all velocity levels a sudden

drop in the heat flow rate was observed. In this sense the results are very similar to the observations made in previous measurements. However, the drop in the heat flow rate was very similar at all velocity levels. This behaviour is very different than the one observed with uncoated surfaces. A possible explanation for the insensitivity of the coated surface onto the air velocity is that no large water droplets could accumulate on the vertically aligned surfaces due to the coating applied on the finned surfaces. This effect of the coating leads to earlier frost formation at all velocity conditions as opposed to the case without coating. So, the applied coating on the finned surface makes them behave very similarly at different air velocity levels. Figure 28 shows the fin tip temperatures. There, the drop in the fin tip temperature was observed at different instants in time. However, the differences in time were a lot less compared to the experiments conducted without coating on the finned surfaces. Figure 29 shows accumulated frost thickness on the fin edges. Here, no considerable differences were observed between different air velocity levels.

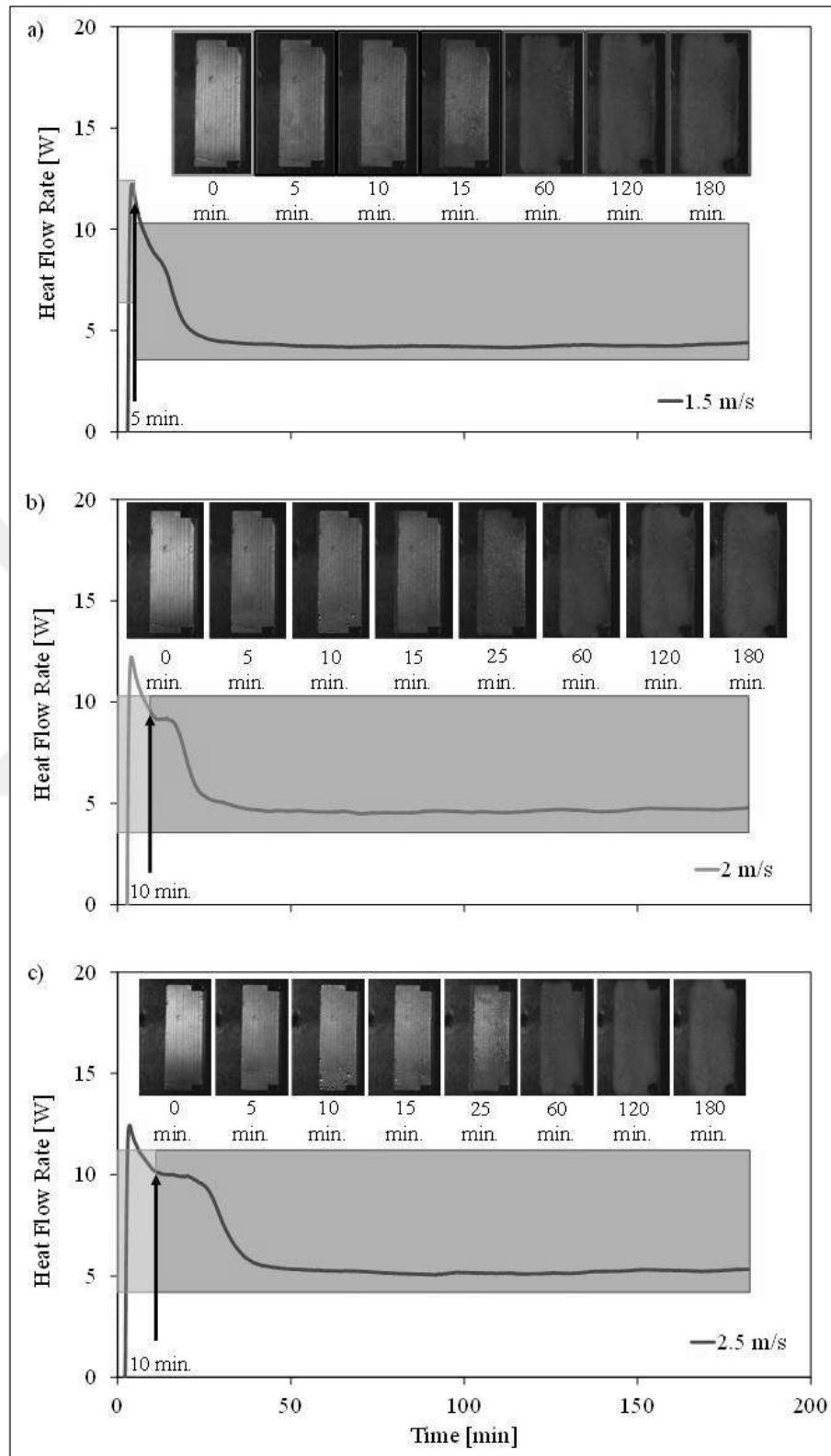


Figure 27. Heat flow rate variations of a) 1.5 m/s b) 2 m/s and c) 2.5 m/s test conditions for V3.

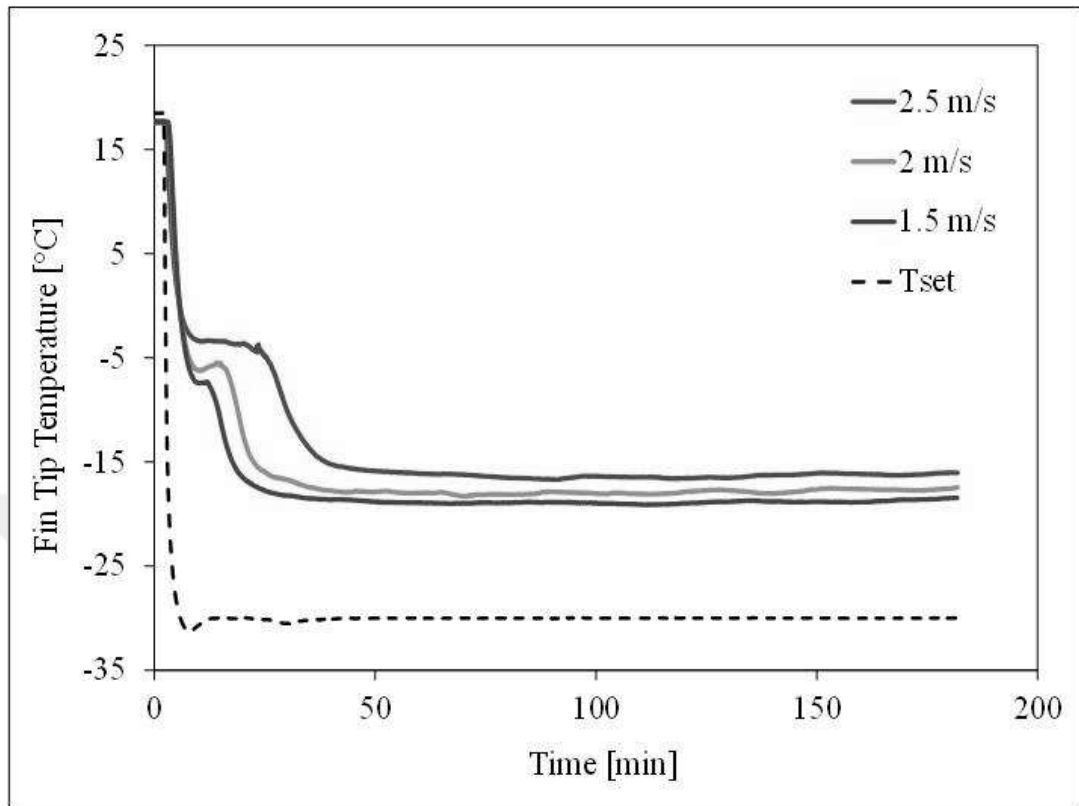


Figure 28. Behaviours of fin tip temperature at different air velocities for the set temperature of $-30\text{ }^{\circ}\text{C}$.

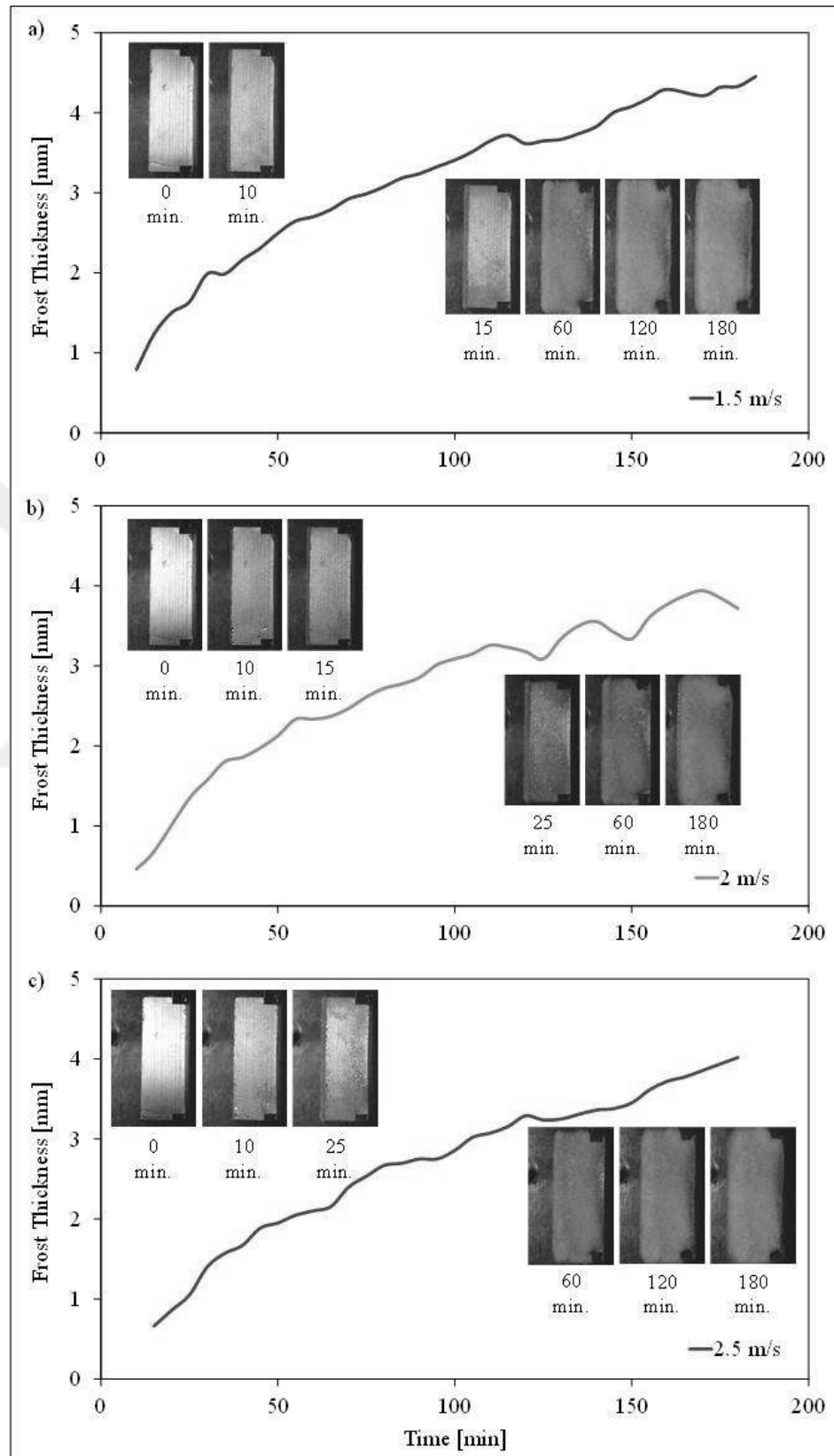


Figure 29. Variation of frost thickness for V3 a) 1.5 m/s b) 2 m/s and c) 2.5 m/s.

4.3 Effect of Fin Space

In this section the effect of fin space on the heat flow rate, fin tip temperature and frost thickness are investigated. Fin spacings were varied between 2 and 6 mm and experiments were conducted at both horizontal alignment under impinging flow conditions and at parallel flow arrangement where the direction of the fins were aligned parallel to the flow direction. Table 5 shows the test conditions.

Table 5. Experimental parameters of different fin space cases

Code	L [mm]	s [mm]	T _{set} [°C]	T _{air} [°C]	Air Velocity [m/s]	RH [%]	Vertical/ Horizontal/Parallel	Coated/Uncoated	Fin Types	AoA [°]
S1	15	2	-30	18	1.5	55	H	Uncoated	Inline	90
		3								
		4								
		5								
		6								
S2	15	2	-30	18	1.5	55	P	Uncoated	Inline	0
		5								
		6								

In these experiments the fin length was kept constant at 15 mm and the temperature at the back surface was set to -30 °C. For all cases the air temperature was kept constants at 18 °C. The orientations of the fins were shown in Figure 30.

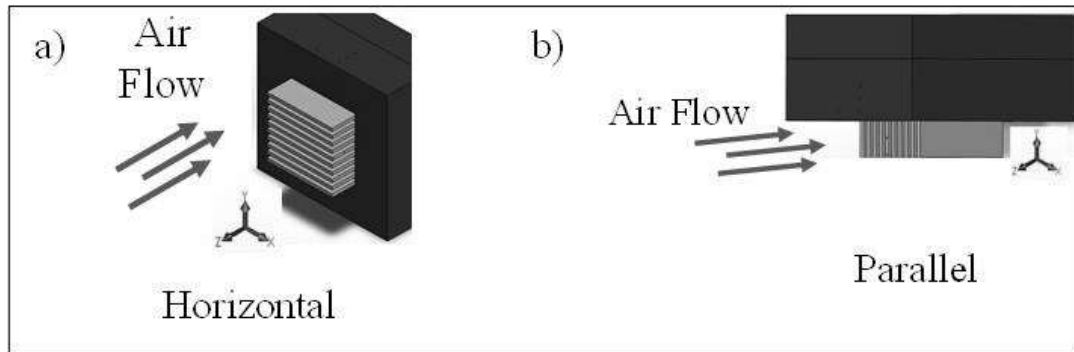


Figure 30. Finned surfaces orientations a) Horizontal and b) Parallel.

4.3.1 S1 Experiments

Monitored heat flow rate through the finned surface was shown in Figure 31 and Figure 32. In all cases, the initial heat flow rate was subject to a drop. The drop in the heat flow rate is associated with the merging of the frost layers on the fins. This blocks the air penetration in between the fins and thereby the effective surface area is considerably reduced. However, the closing of the fin gaps is found to depend on the gap between the fins. The smaller the fin gap the sooner it closes, and the sooner the heat flow rate of the finned surface drops. In all cases, initially liquid water condensation was observed which turns into frost in subsequent stages. The condensation and frosting stages are marked in Figure 32 with green and blue zones respectively. One can see that the duration of the condensation stage is largest at the experiment with a 2 mm fin gap. The fin tip measurements shown in Figure 33 are consistent with this observation. At the initial stage of the experiments the finned surfaces with smaller spacings have higher fin tip temperatures compared to the finned surfaces with larger spacing. The lower fin tip temperatures observed with larger fin spacings cause earlier freezing of the condensed water droplets. The spikes in the tip temperatures that are observed at surfaces with low fin spacings indicate the solidification of the condensed liquid water droplets which is not observed with the 6 mm fin spacing. At 6 mm fin spacing the frosting starts at a very early stage such that no considerable amount of liquid water droplets accumulates on the fin tips.

Figure 34 and Figure 35 show the average frost thickness on the fin tips. In these figures no considerable differences between the rate of increases in the frost thicknesses were observed.

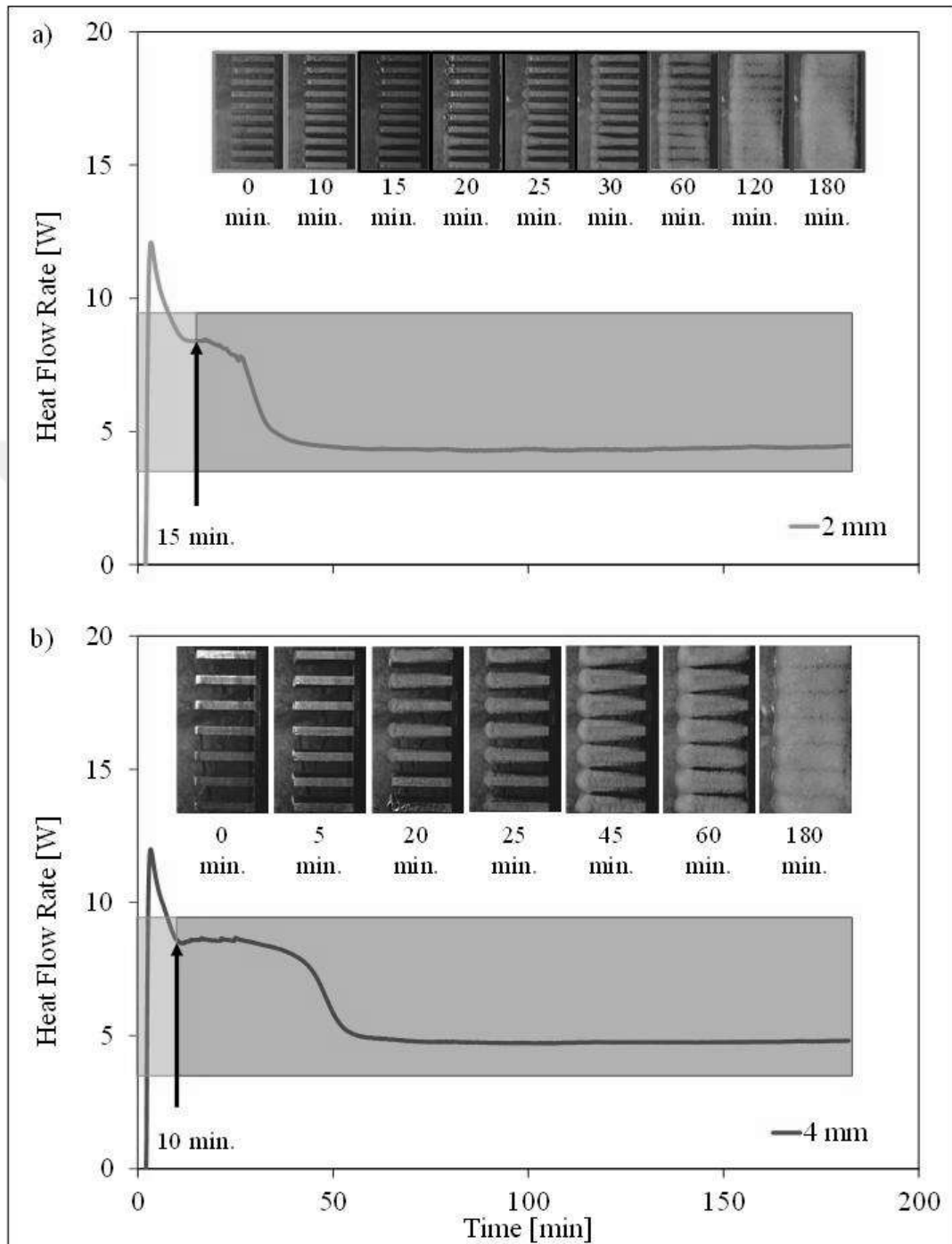


Figure 31. Heat flow rate variations of a) 2 mm and b) 4 mm test conditions for S1.

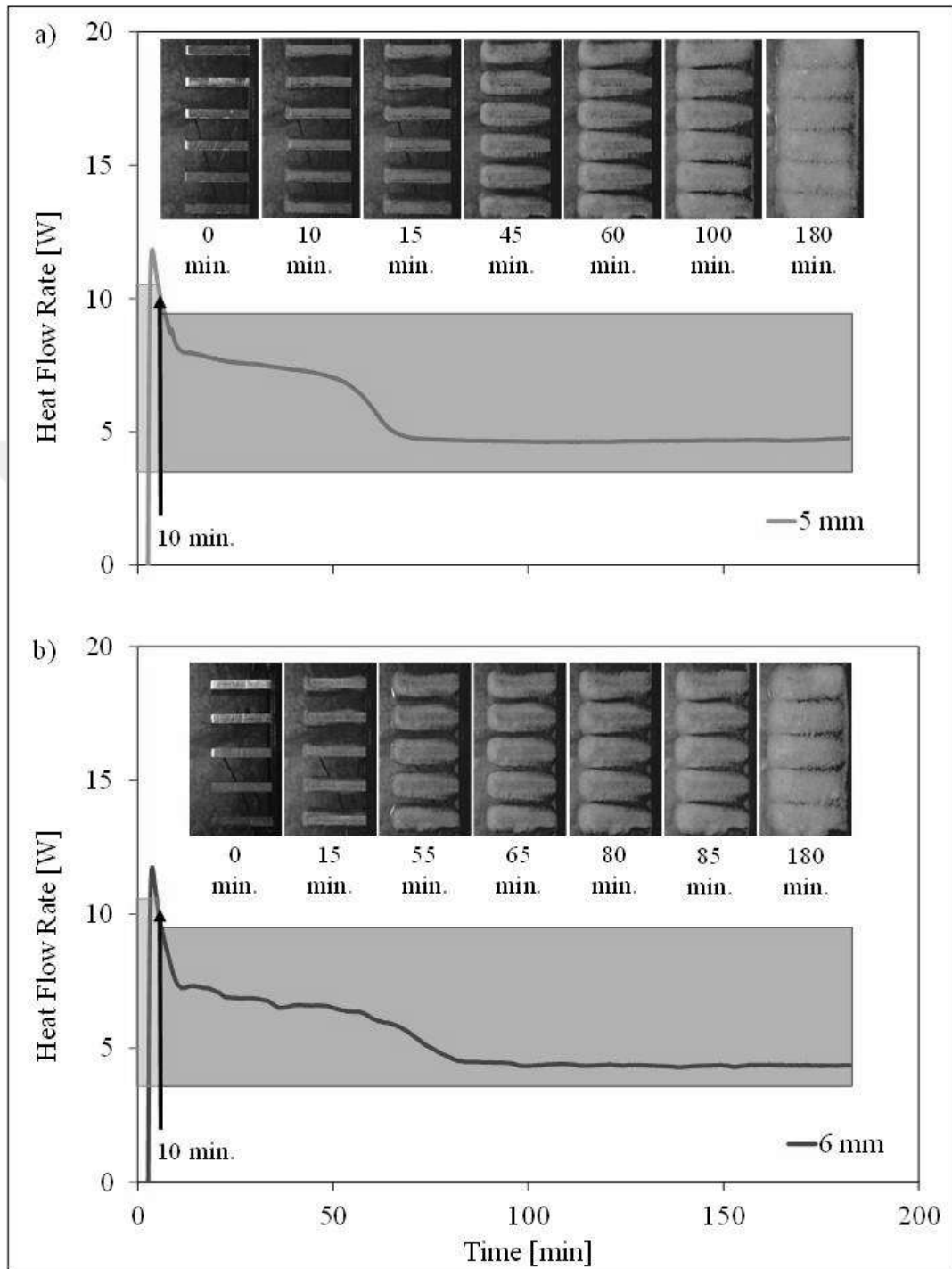


Figure 32. Heat flow rate variations of a) 5 mm and b) 6 mm test conditions for S1.

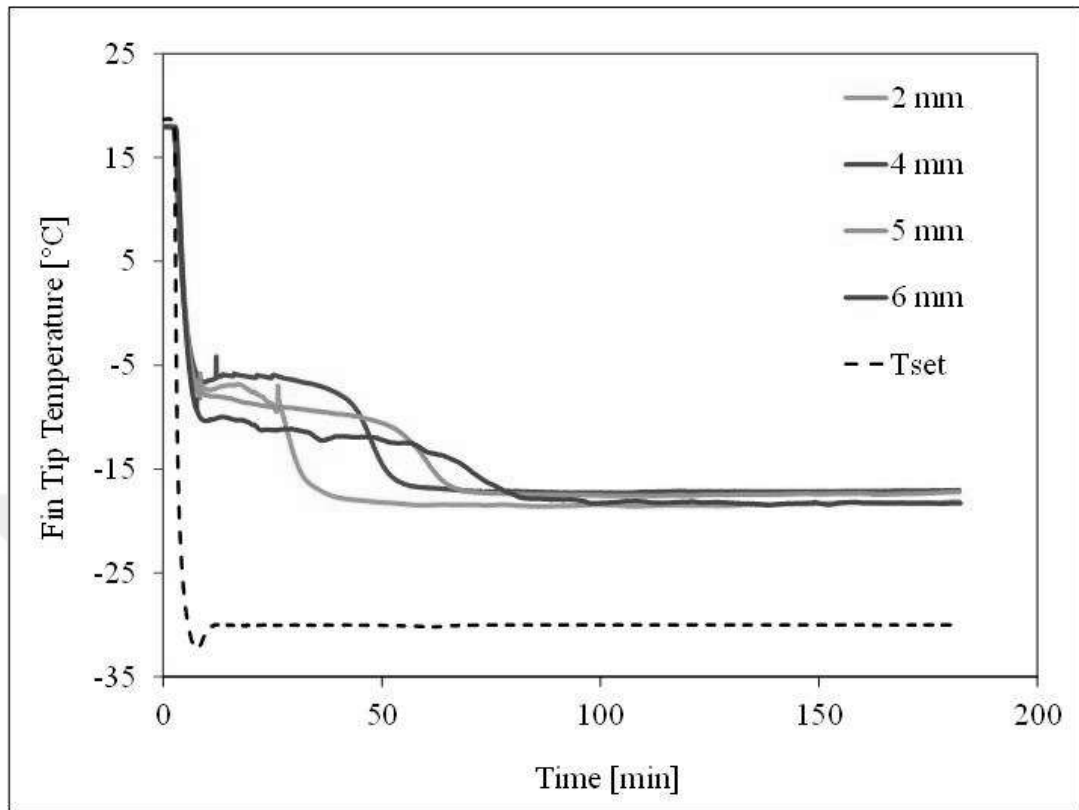


Figure 33. Effect of fin space on fin tip temperature for the set temperature of -30°C and horizontal configuration of fins in the experiment S1.

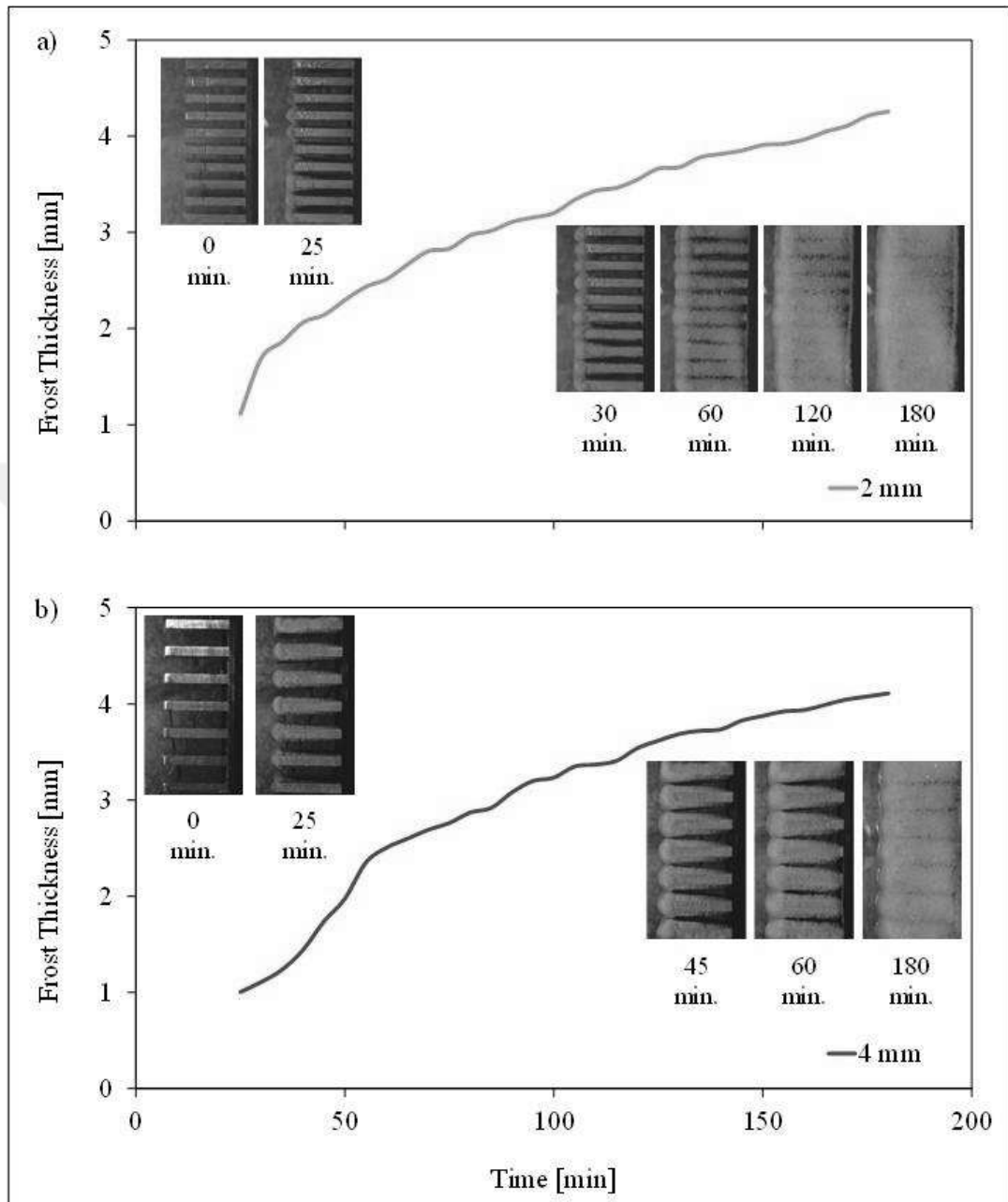


Figure 34. Frost thickness for S1 a) 2 mm and b) 4 mm fin spacings.

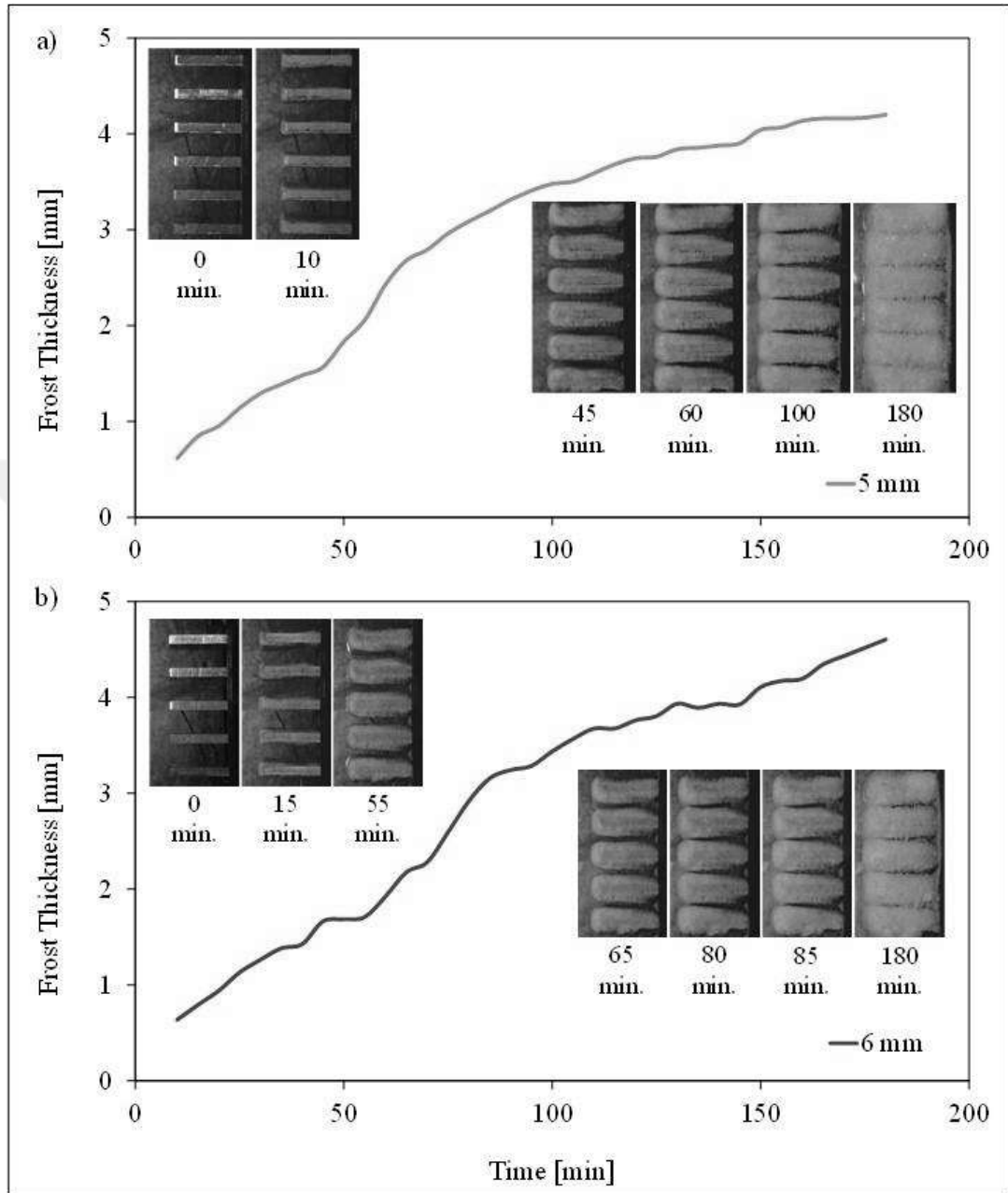


Figure 35. Frost thickness for S1 a) 5 mm and b) 6 mm fin spacings.

4.3.2 S2 Experiments

In these experiments the orientations of the finned surfaces were changed to parallel. Figure 36 shows the heat flow rate into the finned surface during the frosting process. As in the previous configuration a liquid water condensation stage was

observed prior to frost build-up on the fins. The duration of this condensation stage depends on the fin gap size. The smaller the fin gaps the more time it requires until the accumulated water condensates turn into frost. After the initial frost build-up on the fins the frost thickness on the fins steadily increases until the gap between the fins completely close down. This causes a dramatic drop in the heat flow rate into the surface. As in the horizontal configuration, the smaller the fin gaps the sooner the fin gaps close down and the sooner the heat flow rate into the surface drops. Figure 37 shows the fin base temperatures during the measurements. In parallel flow configuration the temperature of the fin base with 2mm fin gap was lowest. However, in horizontal arrangement of the fins the fin base temperature with 2 mm fin gap was higher than the fin base temperatures with 5 and 6 mm fin gaps. The reason for the discrepancy in the fin base temperatures is not clear. However, it is important to point out that the fin base temperature measurements are only conducted at the centre of the finned surfaces. In the parallel flow arrangement, the initial frost growth is observed at the upstream edge of the fins. So, the fin base temperature results do not reflect the temperature of the fin base where initial frost growth was observed. Conducting the measurements on the upstream edge of the fins the results could have been different. Figure 38 shows the frost thickness growth during the experiments. No major differences could be observed in the frost growth rates between different fin gaps.

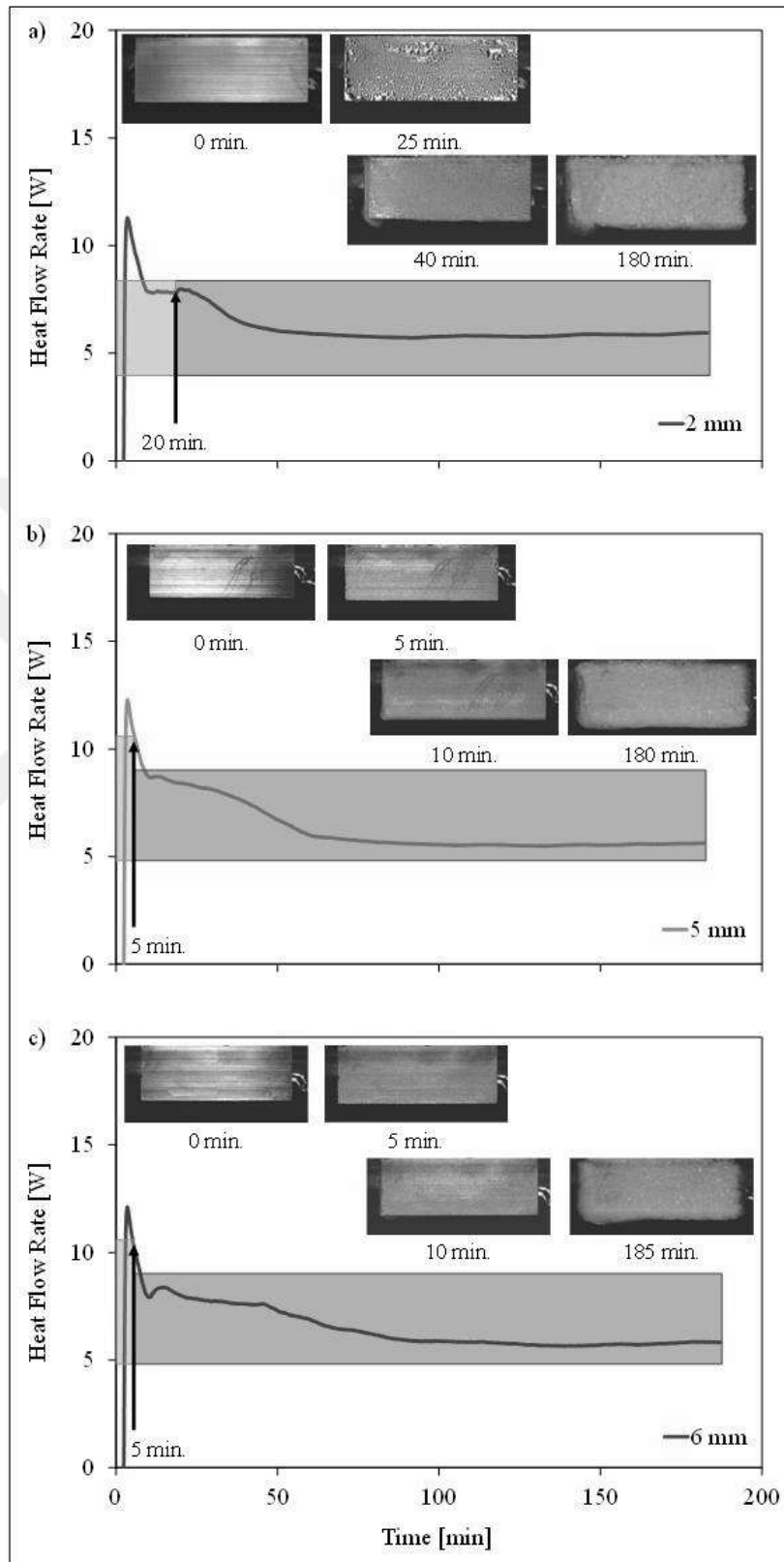


Figure 36. Heat flow rate variations in the experiment S2.

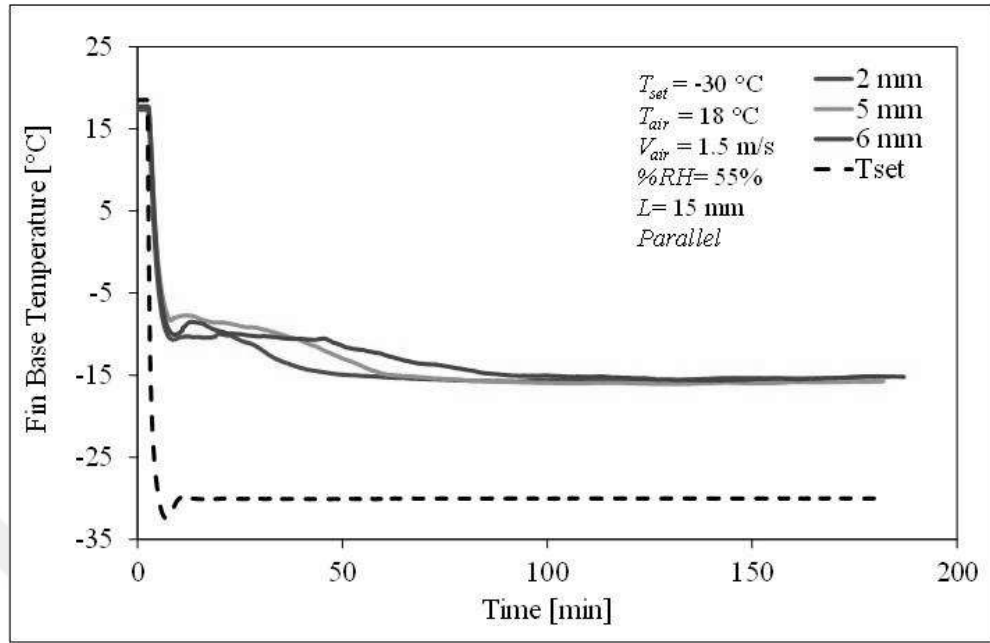


Figure 37. Fin base temperature variation with time of S2 experiments.

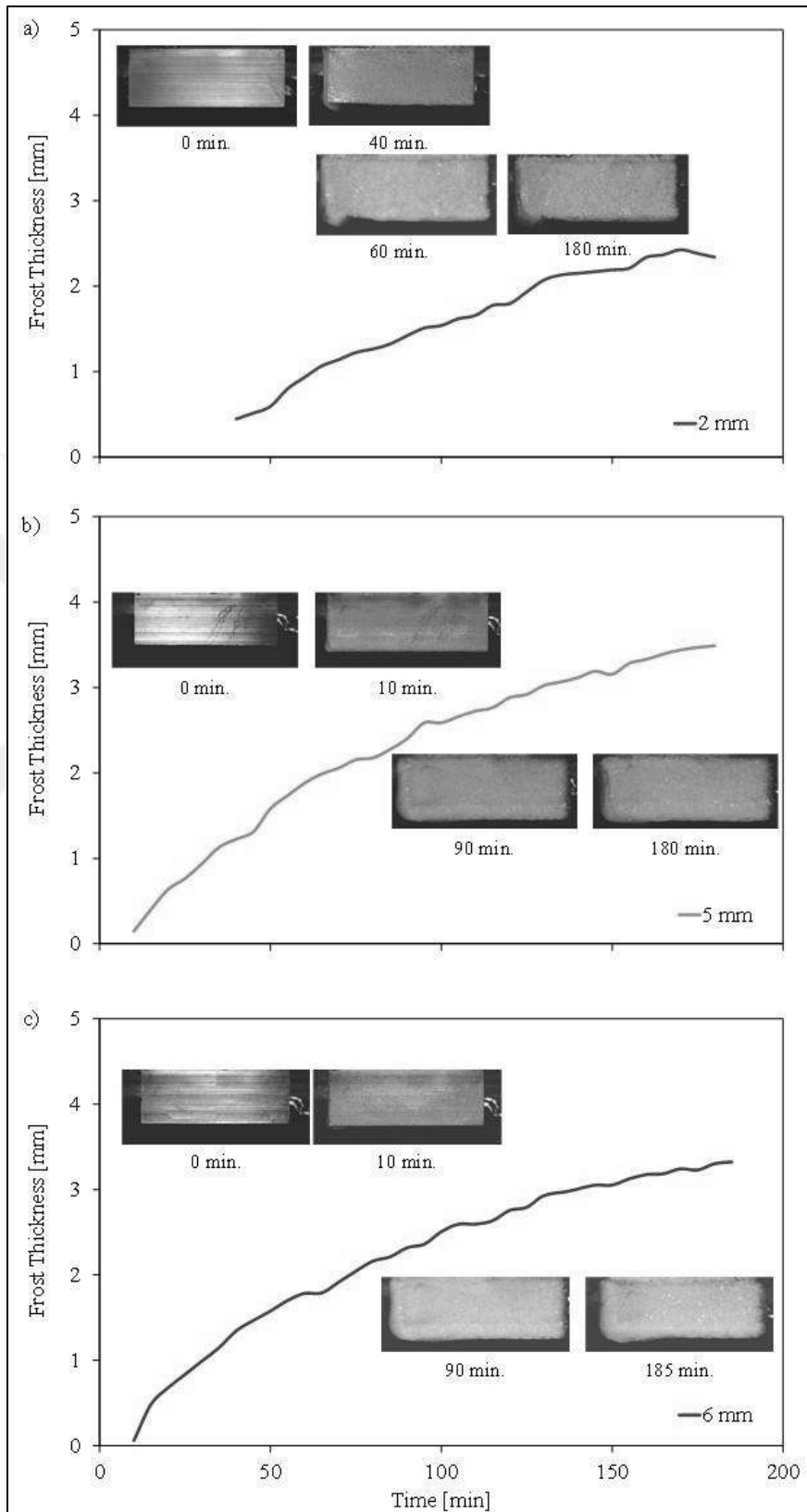


Figure 38. Frost thickness measurements of S2 experiments.

4.4 Effect of Fin Length

The finned surfaces, varying in length from 5 mm to 30 mm, increased by 5 mm and all finned surfaces with the same 2 mm gap, were used to investigate the effects of different lengths on fin performance under frosting conditions. Table 6 shows the DOE for different fin lengths.

Table 6. Experimental conditions of effects of fin length tests.

Code	L [mm]	s [mm]	T _{set} [°C]	T _{air} [°C]	Air Velocity [m/s]	RH [%]	Vertical/ Horizontal/Parallel	Coated/Uncoated	Fin Types	AoA [°]				
L1	5	2	-20	18	1.5	40	H	U	Inline	90				
	10													
	15													
	20													
	25													
30														
L2	5		-30			18	1.5			55	P			0
	10													
	15													
	20													
	25													
30														
L3	5													
	15													

L1, L2 and L3 stand for different experimental conditions. Fin gaps were set to 2 mm at all conditions. The back surface temperatures were set to -20 and -30 °C. Air temperature and velocity were set to 18 °C and 1.5 m/s respectively. Uncoated inline fins were positioned horizontally and parallel to the flow as shown in Figure 39.

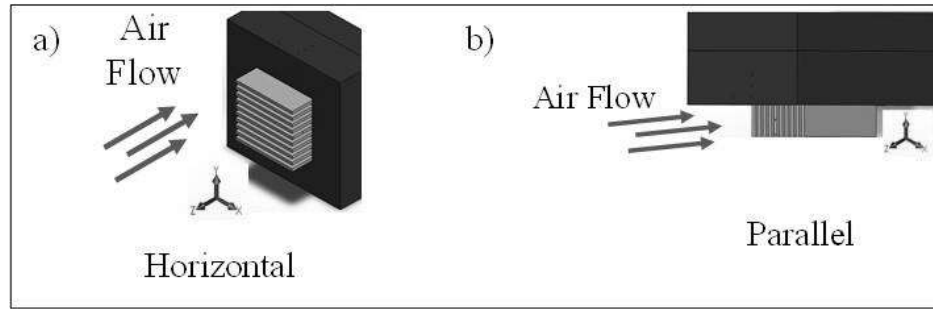


Figure 39. Different fin length effects on frost formation a) Horizontal and b) Parallel surface orientations.

4.4.1 L1 Experiments

In these experiments the back surface temperature was set to $-20\text{ }^{\circ}\text{C}$. Figure 40 shows the heat flow rate, fin tip temperatures and average frost thicknesses and as well as the overall fin effectiveness during the duration of the experiments. Apart from 30 mm fin length frost formation was observed at all fin lengths. The heat flow rate measurements show that the higher the fin lengths the larger are the heat flow rates through the finned surface. The positive correlation between the fin length and the heat flow rate is due to the rise in the overall fin effectiveness with the increase in the fin length. At all fin lengths studied, considerable drops in the heat low rates were observed during the course of the experiments. At low fin length up to 15 mm, the drop in the heat flow rate was mostly due to the closing of the fin gaps with the frost accumulation. At longer fin lengths considerable liquid water condensation was observed on the fins. The accumulated liquid water droplets reduce the air penetration in between the fins which decreases the heat flow rate. After a while the accumulated liquid water droplets turn into frost and at that instance a sharp peak in the heat flow rate was observed. However, the rates of decrease in the heat flow rates before and after the frosting are similar at longer fin lengths. The frost accumulation on the fin surface does not result in

a steeper drop in the heat flow rate. The fin tip temperature measurements show a spike in some of the experiments. The spikes in the fin tip temperature were observed at fins that are longer than 10 mm. The fin tip temperatures at those fin lengths are initially barely below zero. However, after a while the fin tip temperatures reach to about -5°C and then instantly the freezing of the accumulated liquid water droplets occur which causes the spike in the fin tip temperature. The average frost thicknesses during the course of the experiments were also shown in the same figure. As discussed, the frosting starts later with the longer fin lengths. However, after the initial frost formation the rates of increase in the frost thicknesses were also found similar. The photos of the finned surfaces right before the first frost layer was seen and right after the initial frost layer build-up and at the end of the experiment were shown in Figure 41.

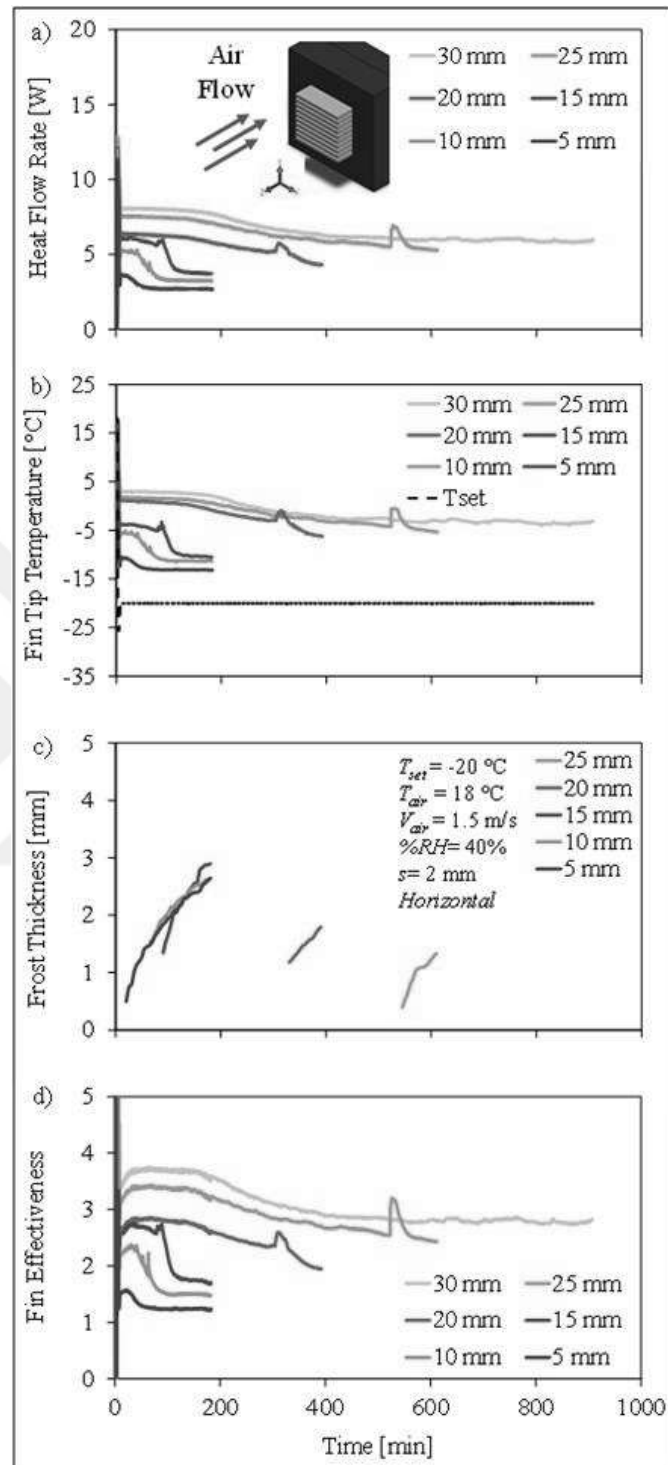


Figure 40. Various performances in L1 tests a) Heat flow rate b) Fin tip temperature
c) Frost thickness and d) Fin effectiveness.

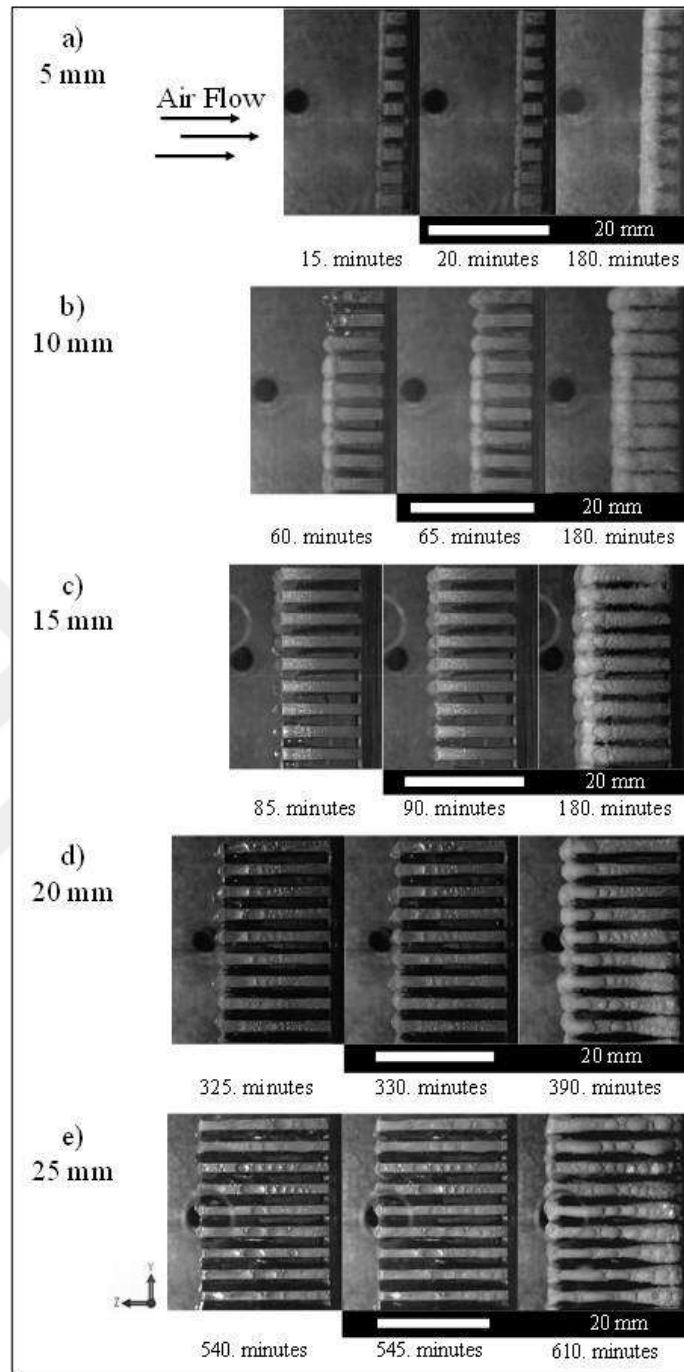


Figure 41. Frost formation process for L1 a) 5 mm b) 10 mm c) 15 mm d) 20 mm and e) 25 mm.

4.4.2 L2 Experiments

The experiments conducted in the previous section were repeated with a lower back surface temperature set to -30°C . The results were shown in Figure 42. In these measurements frost formation was seen at all fin lengths considered. The lower back surface temperature leads to frosting even with 30mm fin length. Similar to the L1 tests, the highest heat flow rate was observed with the longest fin length. However, the surfaces with longer fins also resist considerably more to the drop in the heat flow rate due to the frosting and they keep a higher effectiveness during a longer portion of the duration of the experiment. As shown in the figure, the fin tip temperatures were also correlated with the fin lengths as in the experiments in the previous section. The average frost thicknesses differ with the fin length. However, the difference in the frost thickness is due to the delay in the frosting with longer fins. The rate of increase in the frost thickness after the initial frost formation were found to be similar at the different fin lengths considered. Figure 43 shows the images of the finned surfaces at different instants in time during the experiments.

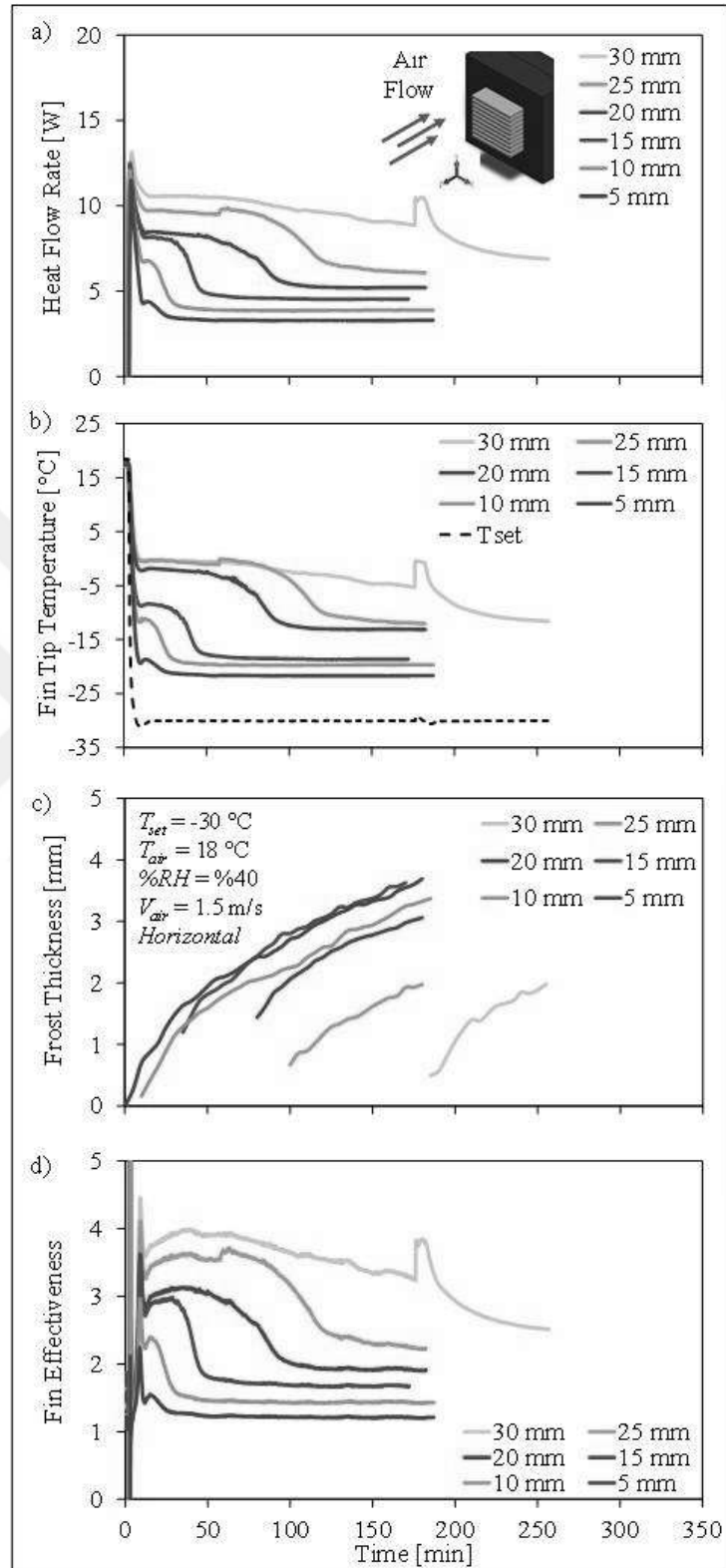


Figure 42. Various performances in L2 tests a) Heat flow rate b) Fin tip temperature
c) Frost thickness and d) Fin effectiveness.

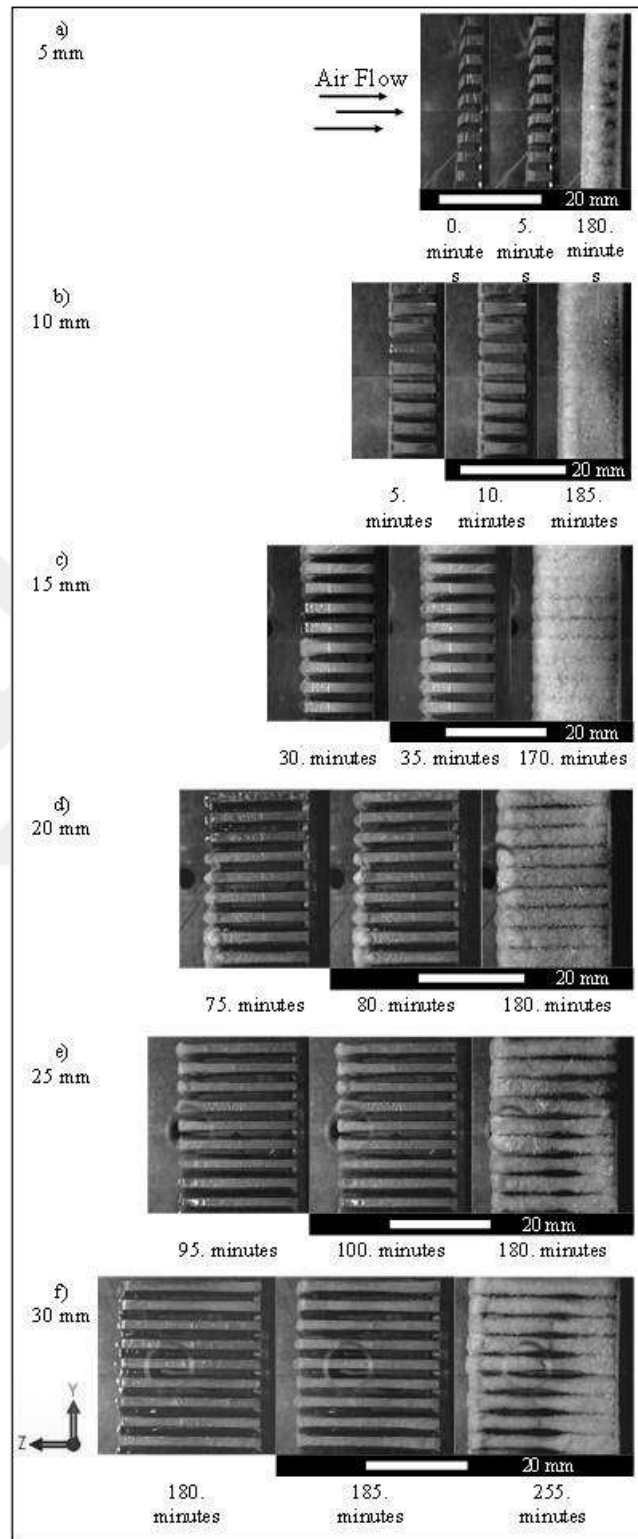


Figure 43. Frost formation process for L2 a) 5 mm fin length b) 10 mm fin length c) 15 mm fin length d) 20 mm fin length e) 25 mm fin length and f) 30 mm fin length.

4.4.3 L3 Experiments

Finally, the effect of the fin length on the heat flow rate has been investigated under parallel flow arrangement where the flow was aligned with the direction of the fins. Figure 44 shows the heat flow rate through the finned surfaces with different fin lengths. In here, it was also found that the finned surface with shorter finned surface was subject to an earlier drop in the heat flow rate. The longer fins caused pronounced liquid condensation on the finned surfaces which delayed the initiation of the frosting process. Moreover, as expected the heat flow rate through the surface with the longer fin lengths was also higher due to the higher total fin surface area. Checking the fin base temperatures shown in

Figure 45 one can also see that the base temperature of the surface with the shorter fins is lower than the one with the longer fins. This observation is consistent with the lower heat flow rate observed with the shorter fin lengths. The lower fin base temperatures caused a more rapid freezing of the condensed water droplets and thereby the fin gaps closed more rapidly than the fin gaps of the longer fins had. Frost thickness measurements shown in Figure 46 show that the frost thickness on the shorter fins is larger due to the earlier onset of the frosting process on the shorter fins. However, the rate of increase in the frost thickness were found to be similar.

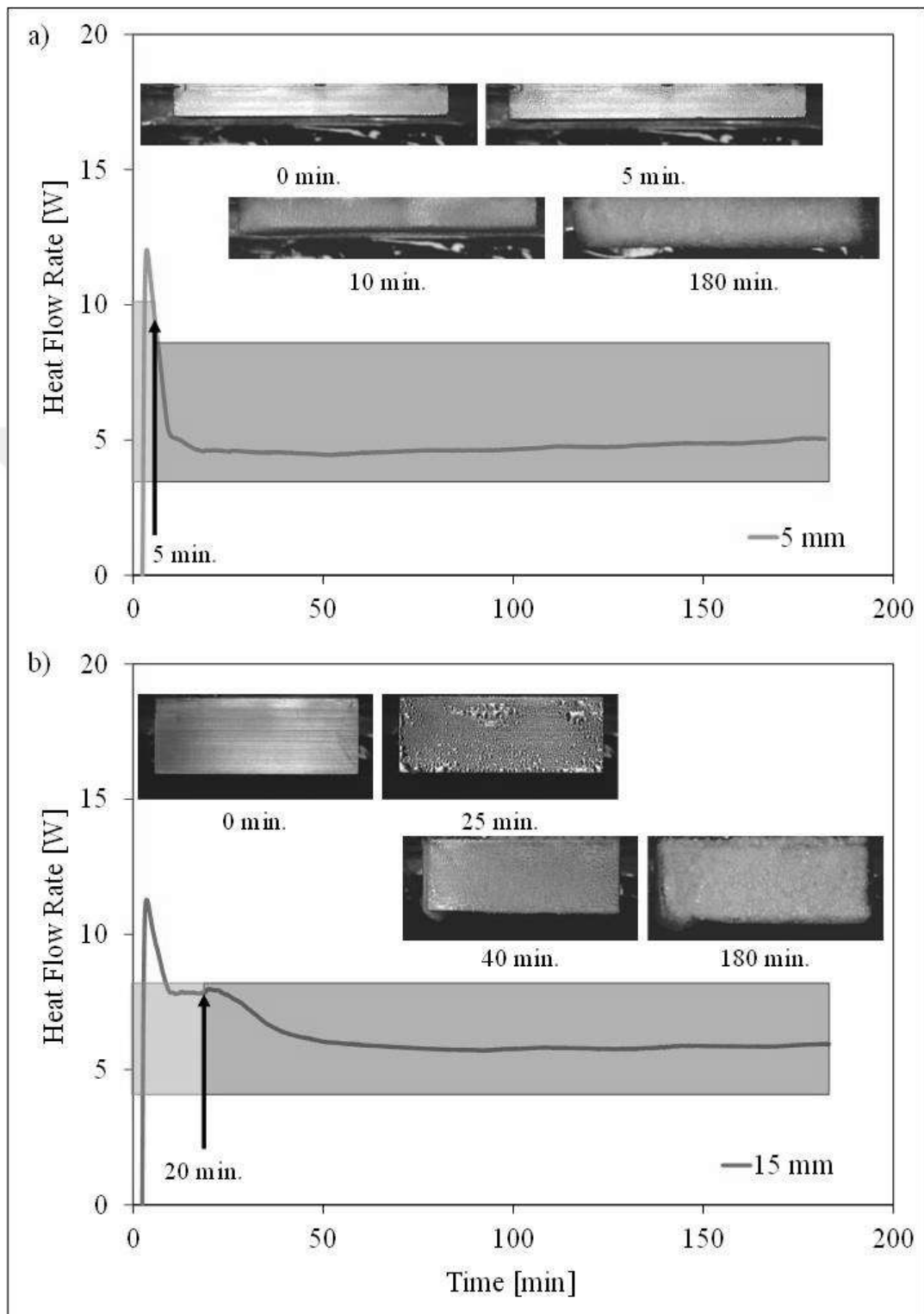


Figure 44. Heat flow rate variations of a) 5 mm and b) 15 mm test conditions for L3.

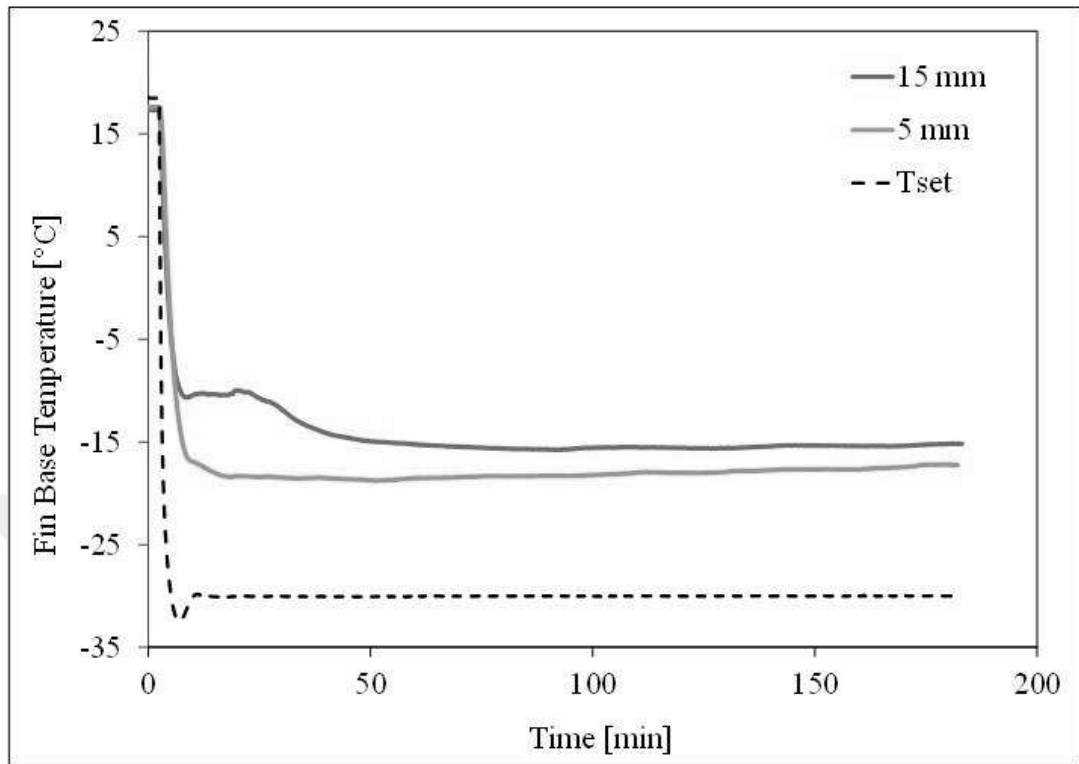


Figure 45. Behaviours of fin tip temperature at different fin lengths for the set temperature of $-30\text{ }^{\circ}\text{C}$.

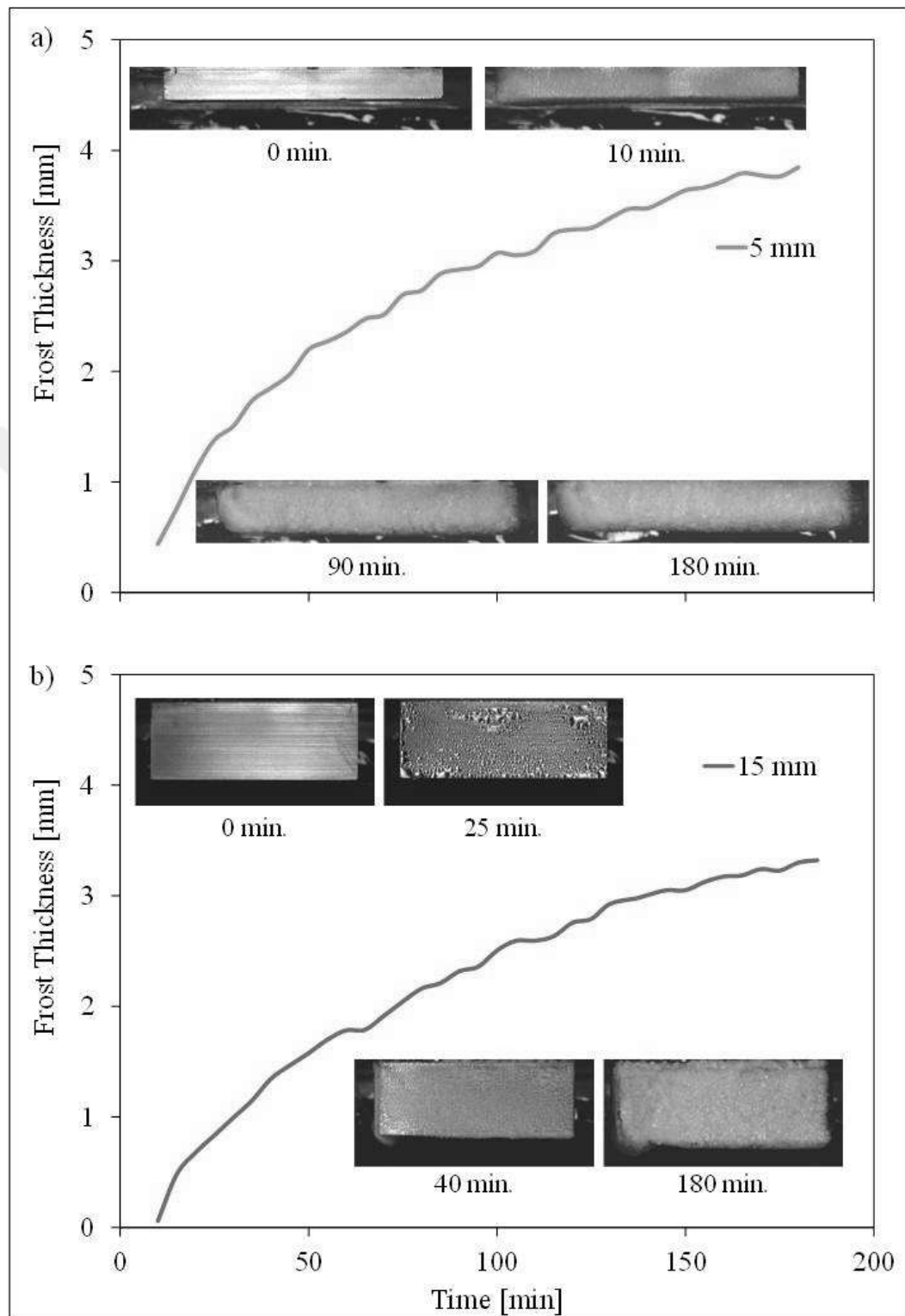


Figure 46. Frost thickness measurements of L3 experiments a) 5 mm and
b) 15 mm fin length.

4.5 Effect of Fin Types

In this section, the effect of fin shape on the heat transfer performance of the finned surface under frosting conditions was investigated. In addition to the inline fin type, staggered and knife edge shaped fins were investigated (Figure 47). The overall fin surfaces and fin thicknesses and gaps of these finned surfaces are the same. Finned surfaces with different fin geometries were tested under parallel, horizontal and vertical flow arrangements (Figure 48). The conditions of the conducted experiments are given in detail in Table 7.

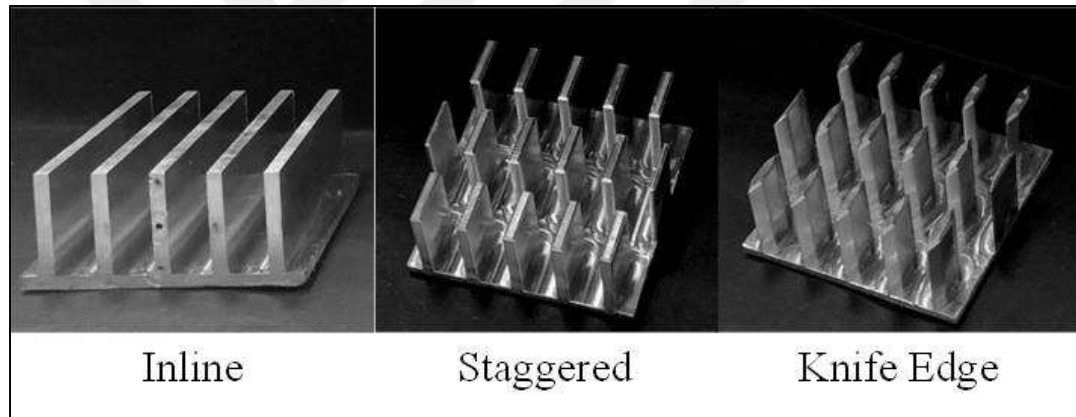


Figure 47. Images of different finned surfaces.

Table 7. Experimental conditions of different fin type cases.

Code	L [mm]	s [mm]	T _{set} [°C]	T _{air} [°C]	Air Velocity [m/s]	RH [%]	Vertical/ Horizontal/Parallel	Coated/Uncoated	Fin Types	AoA [°]
FT1	15	6	-30	18	1.5	55	P	U	Inline	0
									Staggered	
									Knife Edge	
FT2					2				Inline	
									Staggered	
									Knife Edge	
FT3					1.5		H		Inline	90
									Staggered	
									Knife Edge	

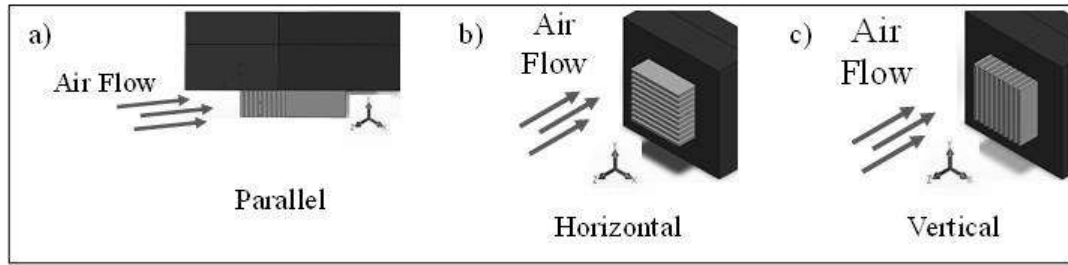


Figure 48. Images of fin orientations a) Parallel b) Horizontal and c) Vertical for different surface types of experiments.

4.5.1 FT1 Experiments

The measured heat flow rates through the finned surfaces are shown in Figure 49. In all fin shapes frosting was observed. The frost accumulation over time also resulted in a drop in the effective surface area of the fins by blocking the air flow between the fins. Inline and staggered fin shapes resulted in similar behaviours in terms of the heat flow rate drops. However, the knife edge shaped fins turn out to be more resistant to the drop in the heat flow rate. The temporal histories of the fin base temperatures are given in Figure 50. There, one can see that the temperature drop rate of the finned surface with the knife edge shaped fins is less than the other finned surfaces do. This also indicates that the heat transfer rate through the knife edge shaped surface is higher than the other two surfaces. At the end of complete frosting the base temperature levels of the three surfaces were very similar to each other. Figure 51 shows the growths of the frost thickness on the finned surfaces. The final frost thickness on the inline fin type was found to be less than the other two. The reasons for this difference are not clear. However, one should also indicate that the average frost thickness on the fins does not truly reflect the actual frost mass accumulated on the surface. So, comparing the overall frost could have been a better way assessment. However, due to the experimental limitations frost mass measurements could not be conducted in the current study.

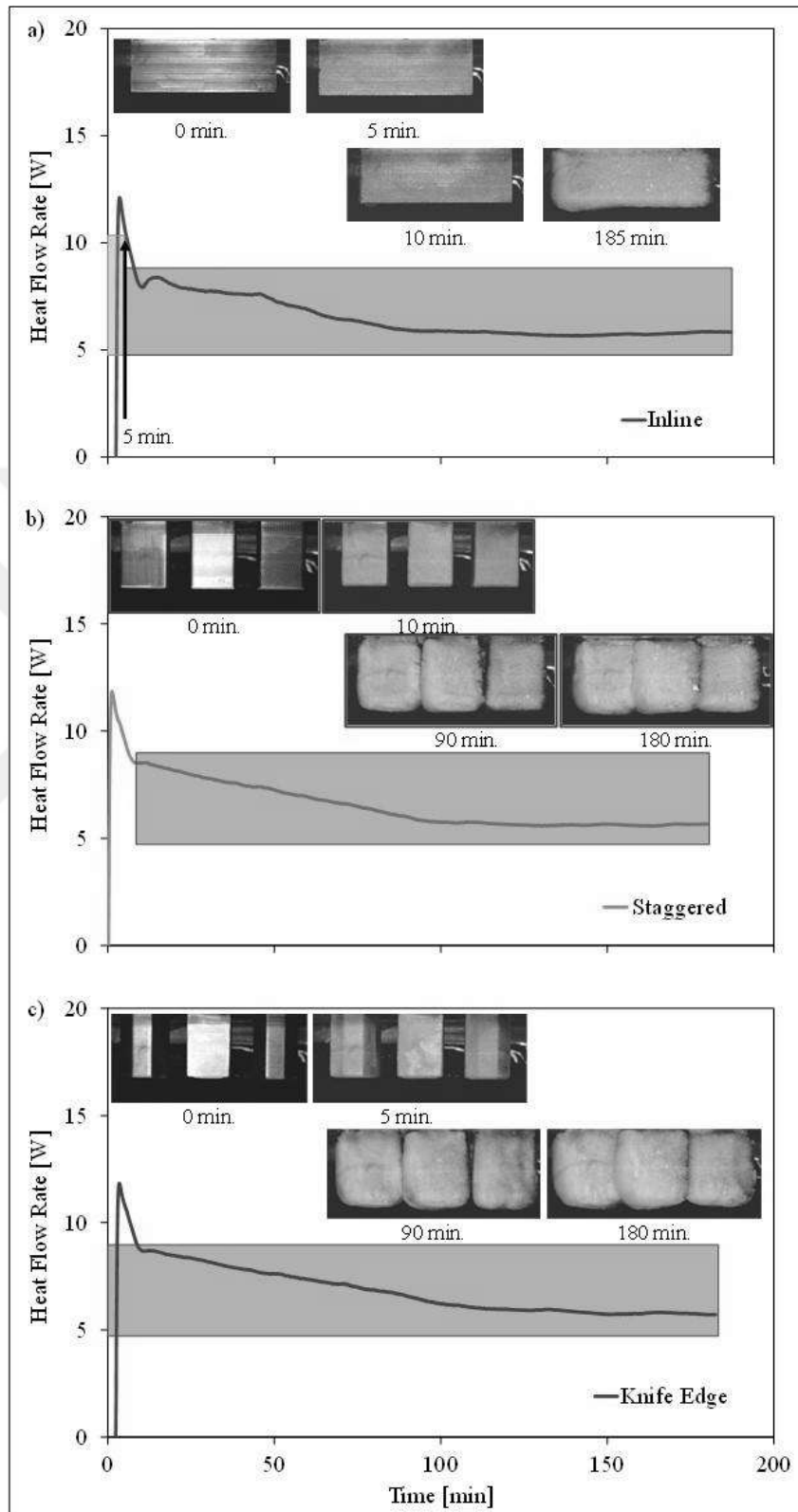


Figure 49. Heat flow rate variation for FT1 experiments a) Inline b) Staggered and c) Knife edge.

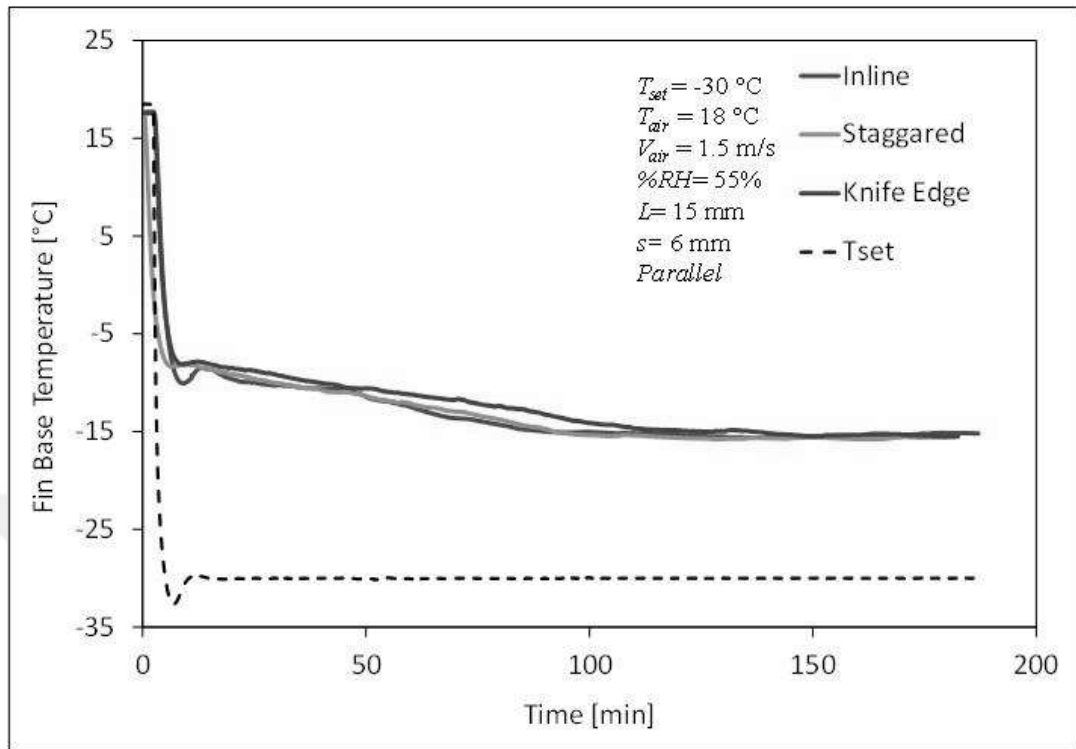


Figure 50. Effects of inline, staggered and knife edge fin type on fin base temperature for FT1.

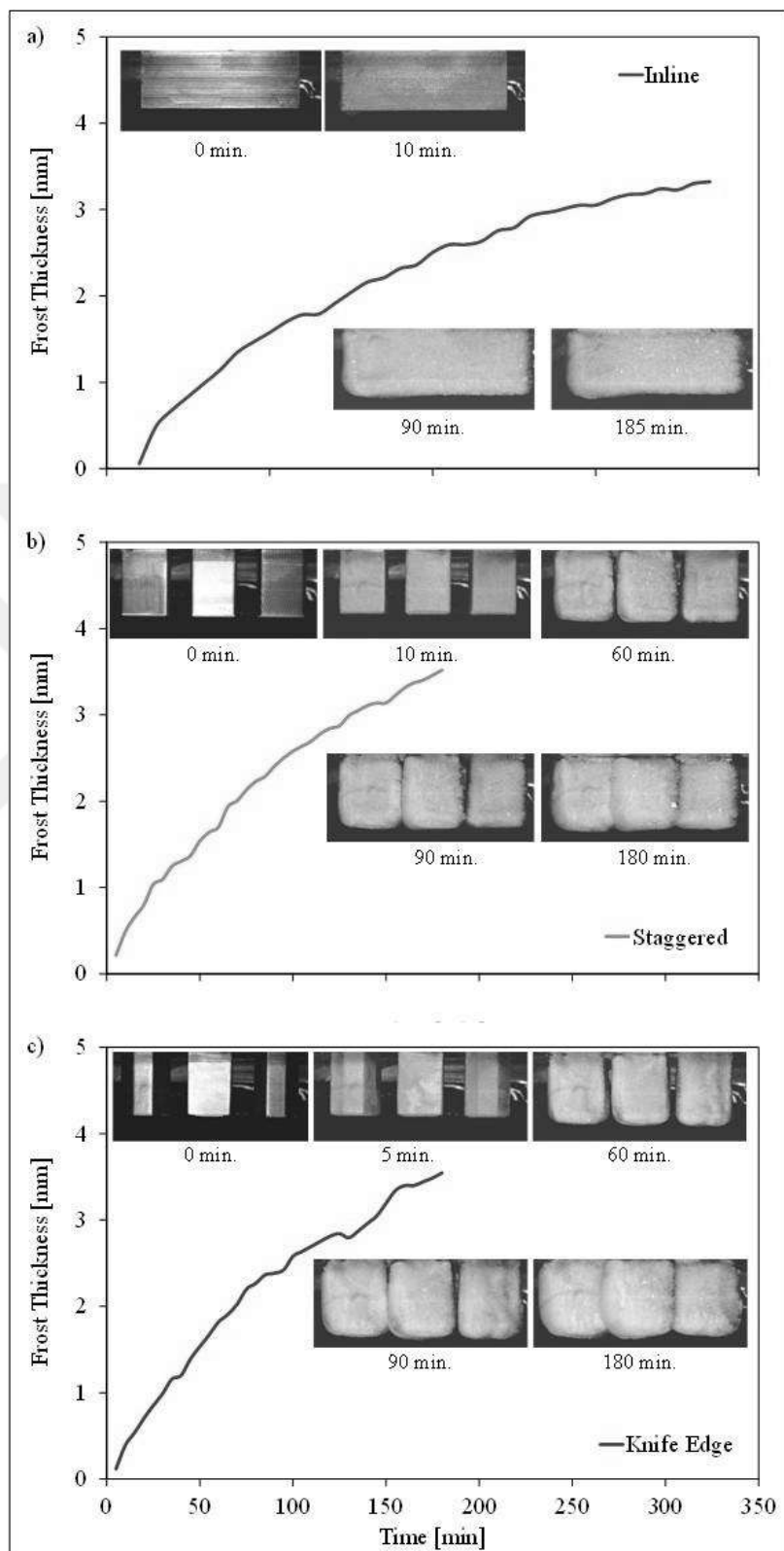


Figure 51. Frost thickness for FT1 a) Inline b) Staggered and c) Knife edge.

4.5.2 FT2 Experiments

In these set of experiments, the air velocity was increased to 2 m/s but other than that the same experimental conditions followed in FT1 were preserved. At this elevated air velocity, no frosting was observed on the knife edge type fins even though the other two fin design were subject to frosting. Figure 52 shows the heat flow rates through the finned surfaces. Since no frosting was observed with the knife edge type fin the level of the heat flow rate was kept similar to its initial value at the beginning of the experiment. Fin base temperature shown in Figure 53 indicates also that the base temperature for the knife edge shaped fin is highest a little bit above -5°C . This temperature level is not sufficient to initiate the frosting process. The reason for the absence of frosting in the knife edge shaped fin is not clear. However, perhaps a larger convective heat transfer coefficient towards the base of the fin and which could have increased the base temperature of the fin. Figure 54 shows the frost thicknesses for the staggered and inline fin types. In those results no considerable differences between the frost thicknesses were observed.

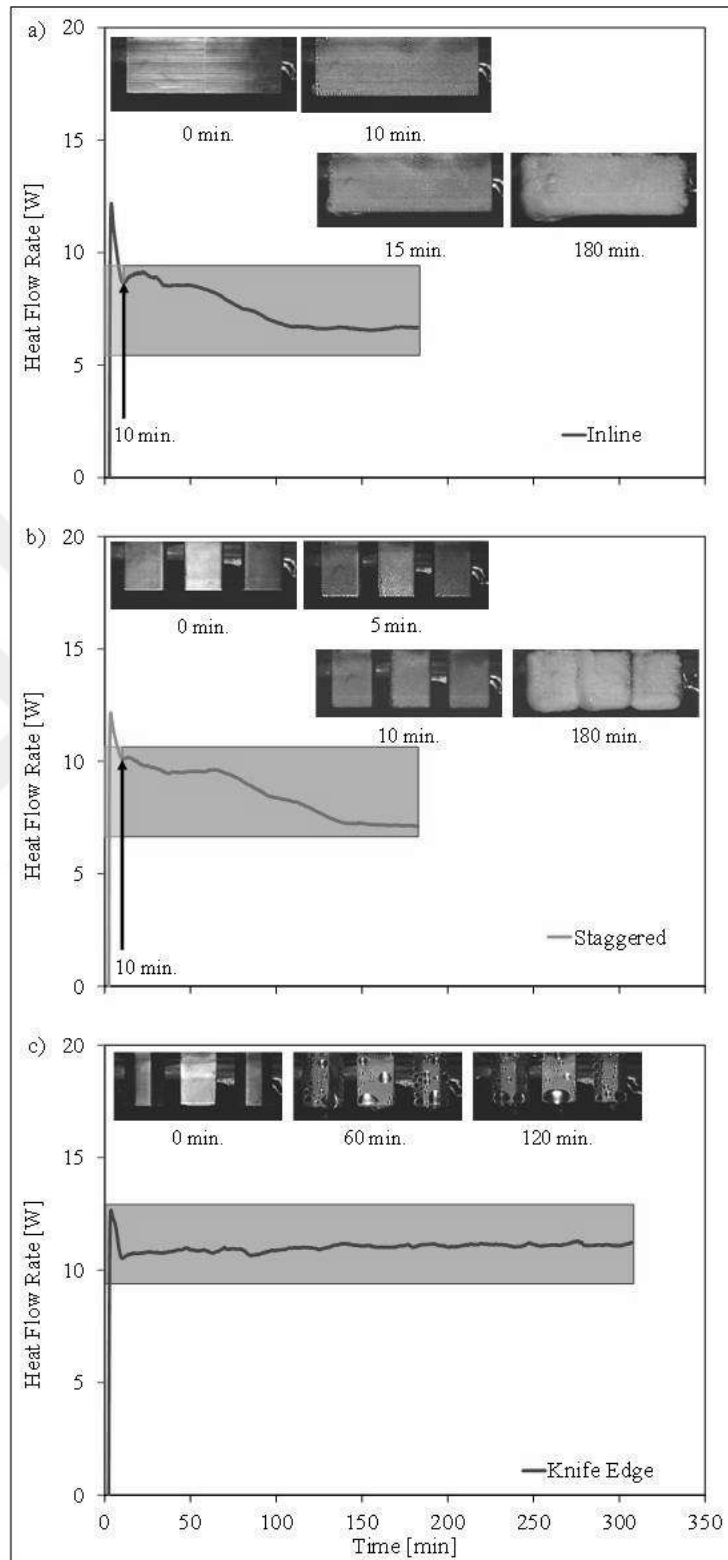


Figure 52. Heat flow rate variation for FT2 experiments a) Inline b) Staggered and c) Knife edge.

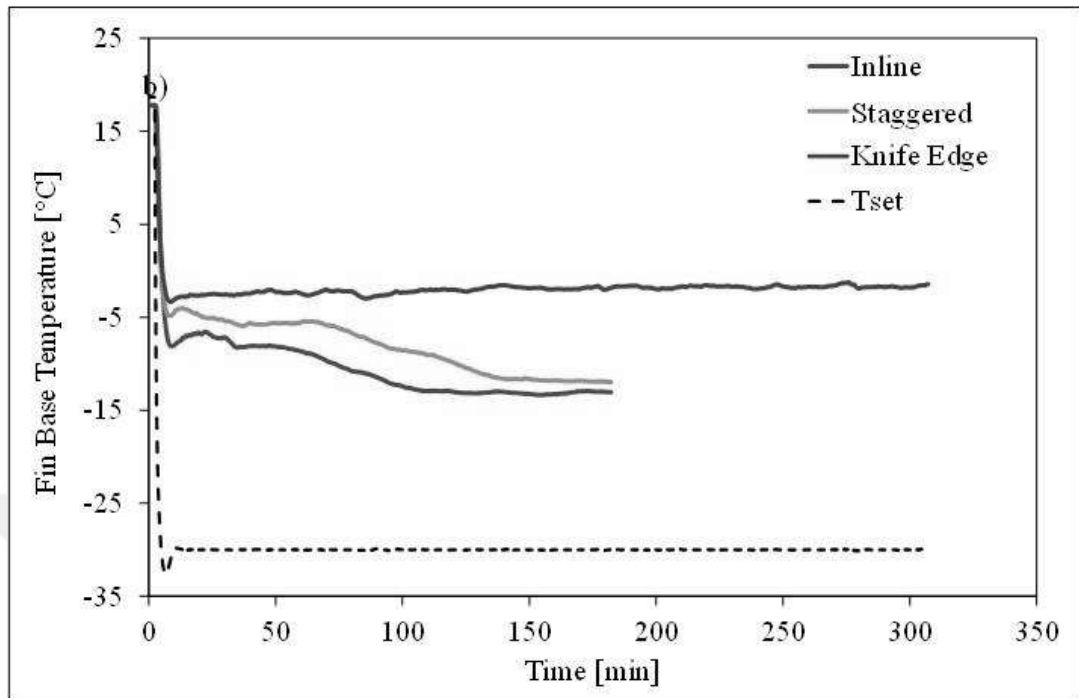


Figure 53. Effects of different fin types in FT2 for fin tip temperature.

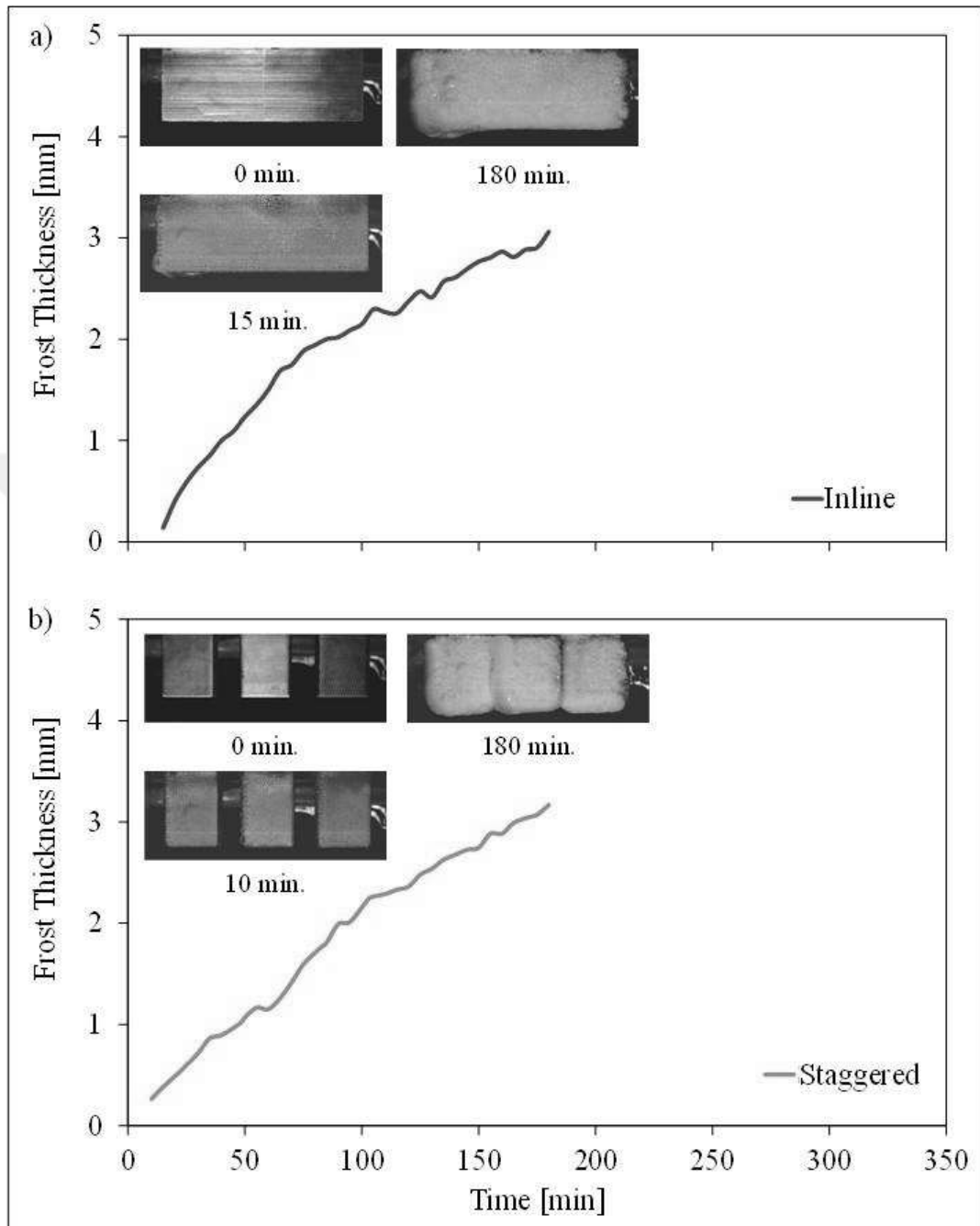


Figure 54. Frost thickness of the experiments for FT2 a) Inline fins and
b) Staggered fins.

4.5.3 FT3 Experiments

In this part, the orientation of the fins was changed to horizontal where the fins are aligned horizontally and the air flow is set to impinge on the finned surface. Figure 55

shows the heat flow rate through the finned surfaces. In these experimental conditions frosting was observed on all fin shapes. This could also be derived from the sharp drop in the heat flow rates. Comparing the three fin shapes one can easily see that the inline fin was subjected to frosting earlier than the other two surfaces were. Parallel to that observation one can also see in Figure 56 that the base temperature of the inline fin is lowest among the three shapes. One explanation for that behaviour is that inline fin shape leads to highest convective heat transfer coefficient compared to the other two fin shapes. One can also see a slight difference in the base temperatures of the other two fin shapes. Overall, the knife edge shaped fins are more resistant to the heat flow rate drop under frosting conditions. Regarding the frost layer thicknesses shown in Figure 57, one can say that there are no major differences in the frost thickness between the three fin shapes.

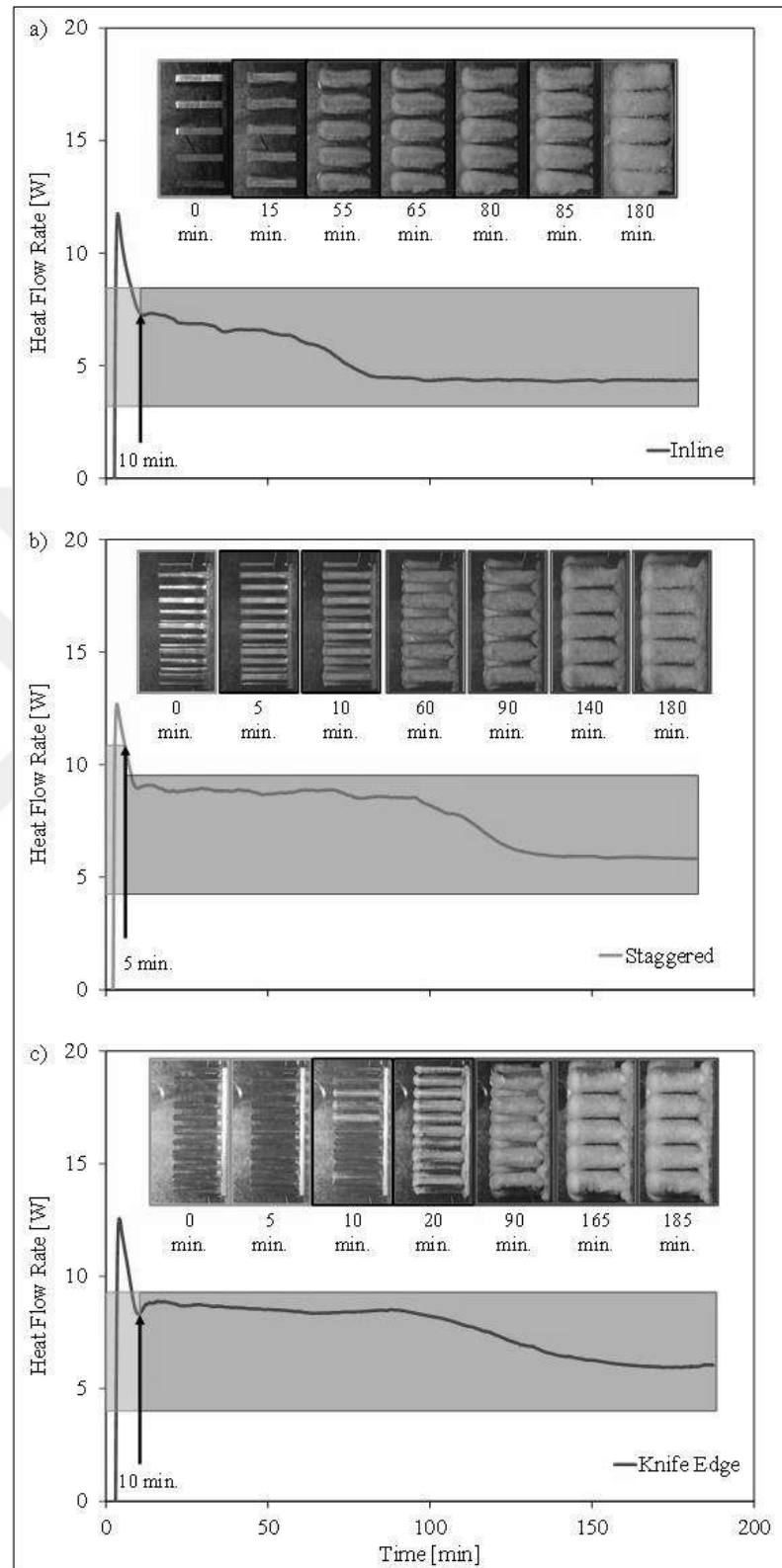


Figure 55. Frost formation for FT3 a) Inline b) Staggered and c) Knife edge.

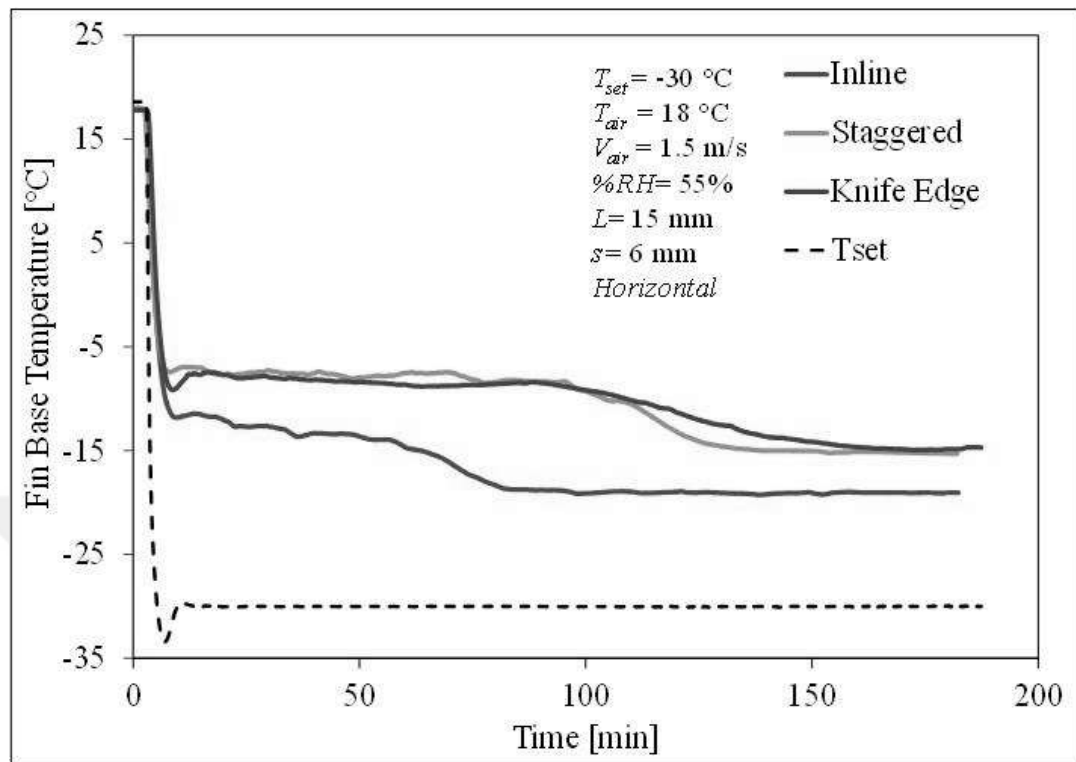


Figure 56. Fin base temperatures at different fin types for $-30\text{ }^{\circ}\text{C}$.

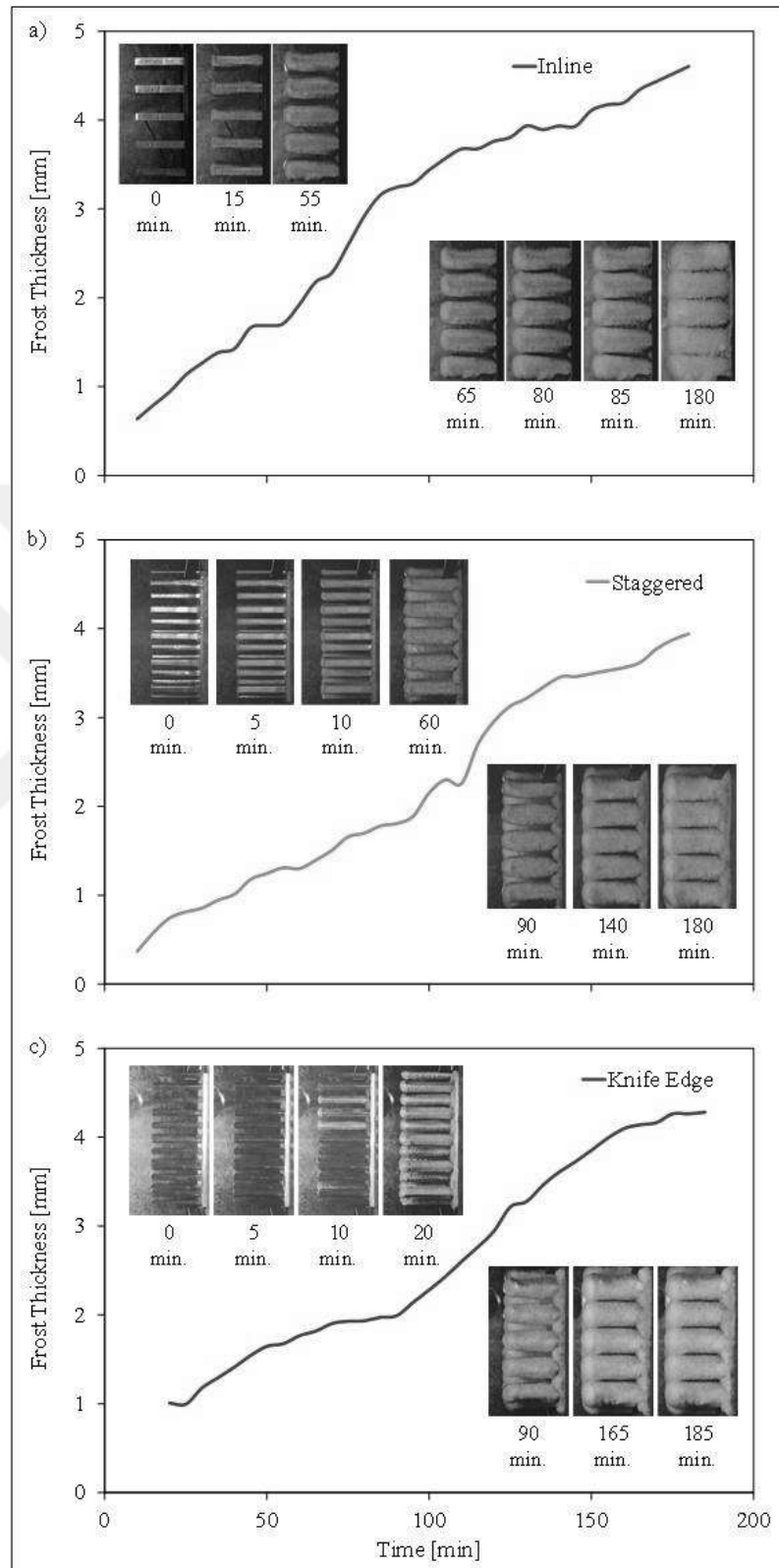


Figure 57. Frost thickness of experiments for FT3 a) Inline b) Staggered and c) Knife edge fin type.

4.6 Effect of Fin Alignment

In this section, the effect of the fin alignment on the heat transfer of the surface is going to be discussed. The test matrix is shown in Table 8. Accordingly, the finned surfaces were tested at three different orientations that are the vertical and horizontal arrangements of the fins which were both tested under the impinging flow conditions. Also tests in parallel flow arrangement were also conducted. The schematic of the orientations were given in Figure 58.

Table 8. Parameters of surface alignment experiments.

Code	L [mm]	s [mm]	T _{set} [°C]	T _{air} [°C]	Air Velocity [m/s]	RH [%]	Vertical/ Horizontal/Parallel	Coated/Uncoated	Fin Types	AoA [°]
A1	15	2	-30	18	1.5	55	Vertical	U	Inline	X
							Horizontal			
							Parallel			

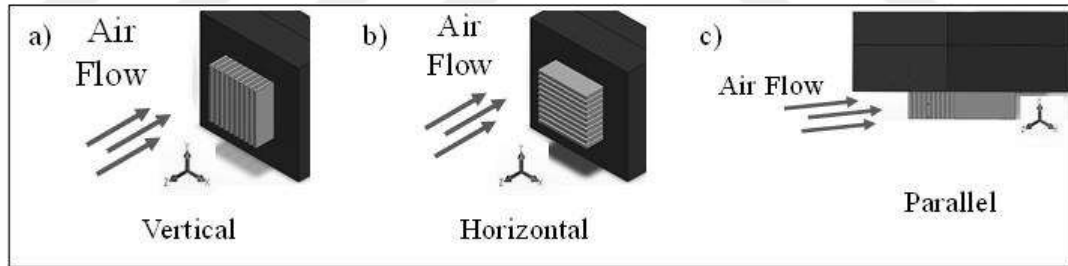


Figure 58. Surface orientations of different fin alignments.

4.6.1 A1 Experiments

Figure 59 shows the heat flow rates through the finned surfaces held at different orientations. In all the configurations frost accumulation on the surface was observed. The accumulated frost also led to the closing of the fin gaps which reduced the effective surface area of the finned surface. This resulted in a drop in the heat flow rate which is present in all three configurations. However, the drop in the heat flow rate shows variations according to the orientation of the surface. Accordingly, the finned surface at

horizontal configuration shows the highest drop in the heat flow rate and provides the lowest heat flow rate through the surface. On the other hand, keeping the same surface parallel to the air flow results in a lower reduction in the heat flow rate. The highest heat flow rate is observed at this orientation of the surface. At the parallel flow configuration, the frost accumulation on the fins results in a relatively lower reduction in the heat flow rate. Figure 60 shows the fin base temperature during the experiments. As shown, the fin base temperature at the parallel flow configuration is highest compared to the other configurations. Higher fin base temperature indicates a higher heat flow rate which was observed in Figure 59.

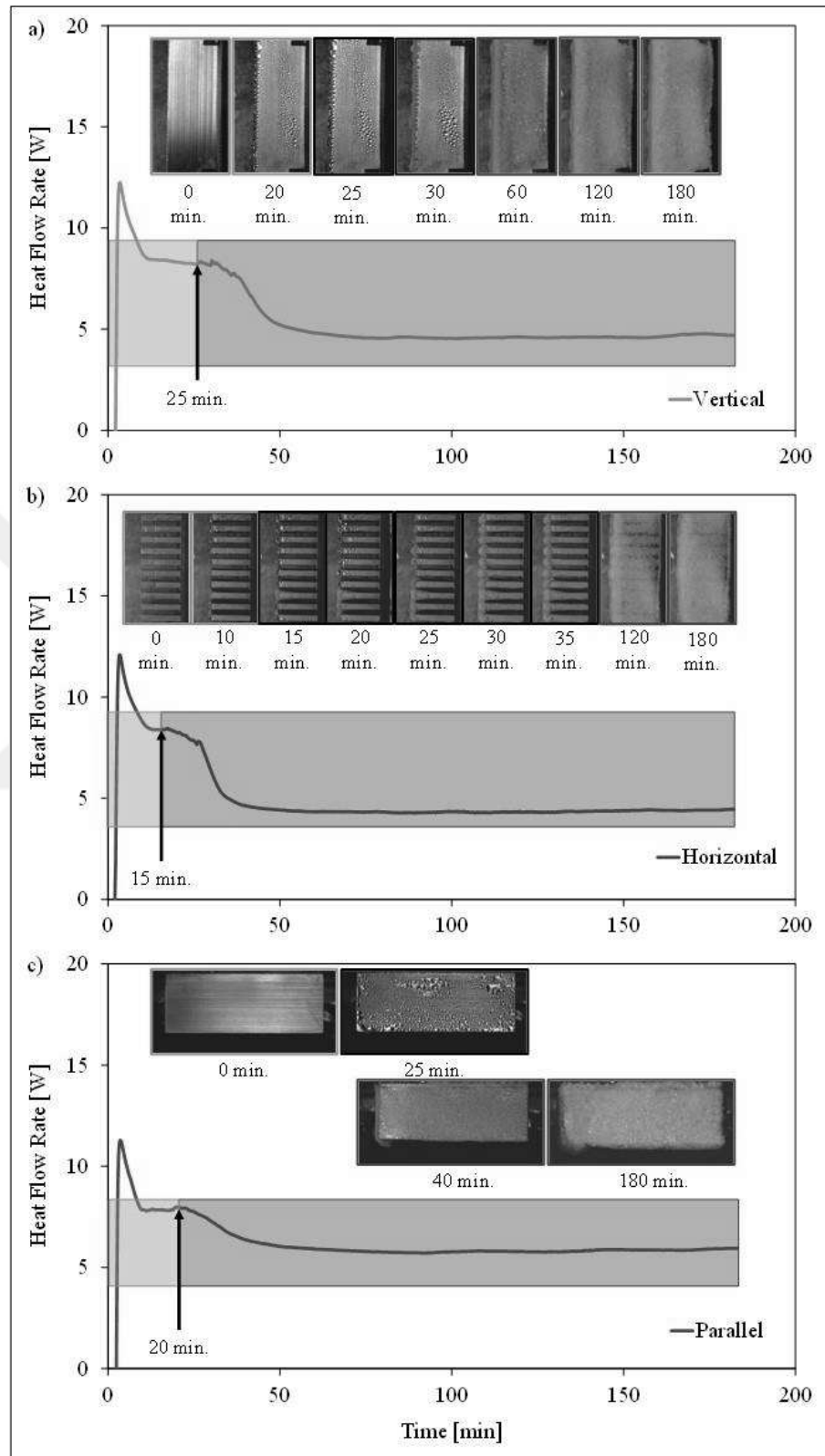


Figure 59. Heat flow rate variations of a) Vertical b) Horizontal and c) Parallel orientations for A1 experiments.

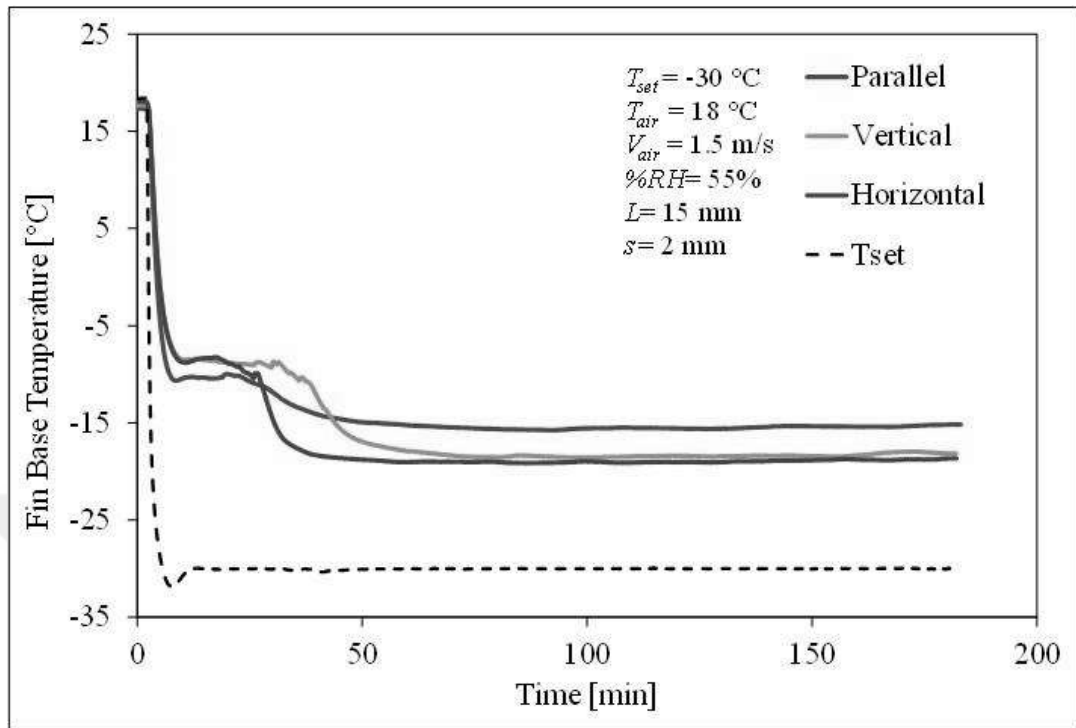


Figure 60. Fin base temperature at different alignments for -30 °C.

4.7 Effect of Coating

In this section, the effect of the superhydrophobic coating on the heat transfer rate through the finned surface under frosting conditions is going to be investigated. The finned surface with 15 mm fin length and 2 mm fin gap was coated with a superhydrophobic coating. Coated finned surfaces were compared with the uncoated finned surfaces under frosting conditions and at different orientations of the surface which are shown in Figure 61. Table 9 shows the parameters of the conducted experiments.

Table 9. Surface treatment cases experimental parameters.

Code	L [mm]	s [mm]	T _{set} [°C]	T _{air} [°C]	Air Velocity [m/s]	RH [%]	Vertical/ Horizontal/Parallel	Coated/Uncoated	Fin Types	AoA [°]
C1	15	2	-30	18	1.5	55	V	Coated	Inline	90
								Uncoated		
C2					2			Coated		
								Uncoated		
C3	15	2	-30	18	1.5	55	P	Coated	Inline	0
								Uncoated		

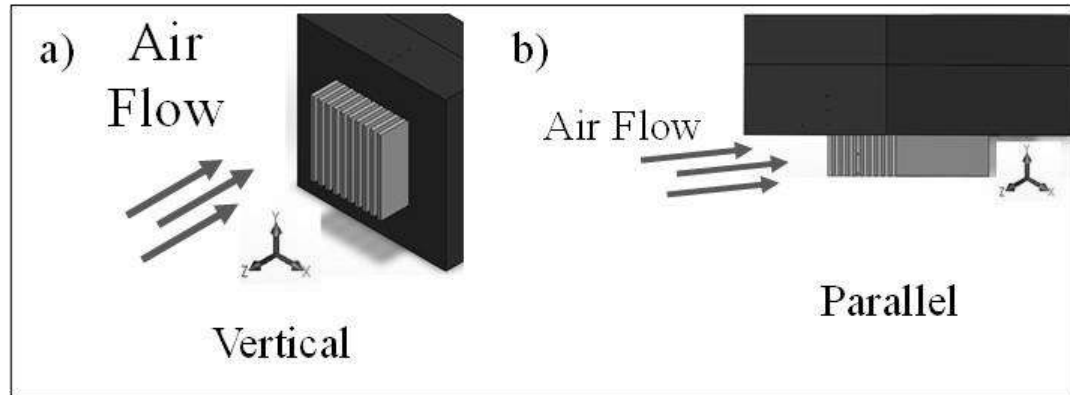


Figure 61. Images of fin orientations a) Vertical and b) Parallel for coated surface experiments.

4.7.1 C1 Experiments

The heat flow rates through the coated and uncoated finned surfaces were shown in Figure 62. Coated and uncoated finned surfaces showed almost the same heat flow rate at the beginning of the experiments. Liquid water condensation was observed on the finned surface without coating. However, no considerable liquid water condensation was observed with the coating since water droplets could not stick to the surface but slide down from the surface. The lower liquid mass on the finned surface with coating is found to be subject to frosting much earlier on than the surface without coating. Figure 63 shows the fin tip temperatures on the surfaces with and without coating. Due to the early frosting on the surface with coating the fin tip temperature drops earlier on in the presence of the coating. Once both surfaces were covered with frost a slight difference in the tip temperatures was still observed. The fin tip temperatures on the coated surface was measured to be around 1°C colder. This observation is consistent with the heat flow rate measurements which show that the heat flow rate through the coated surface is slightly lower than through the uncoated surface. Figure 64 shows the average frost thickness on the fin tips. The results show that the uncoated surface has a lower frost thickness as compared to the coated surface. However, this difference is mainly due to the late frost initiation at the uncoated surface.

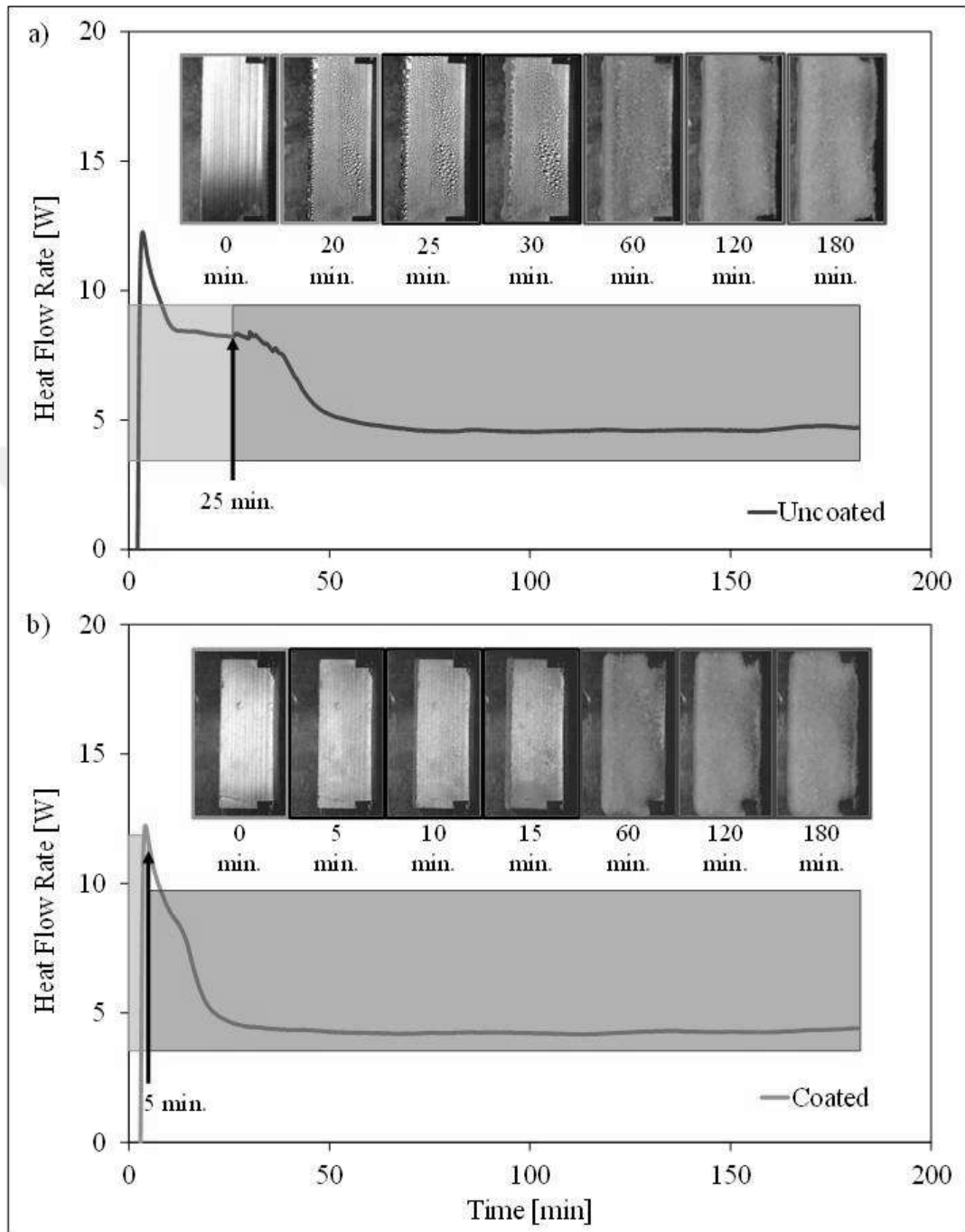


Figure 62. Heat flow rate variations of a) Uncoated and b) Parallel orientations for C1 experiments.

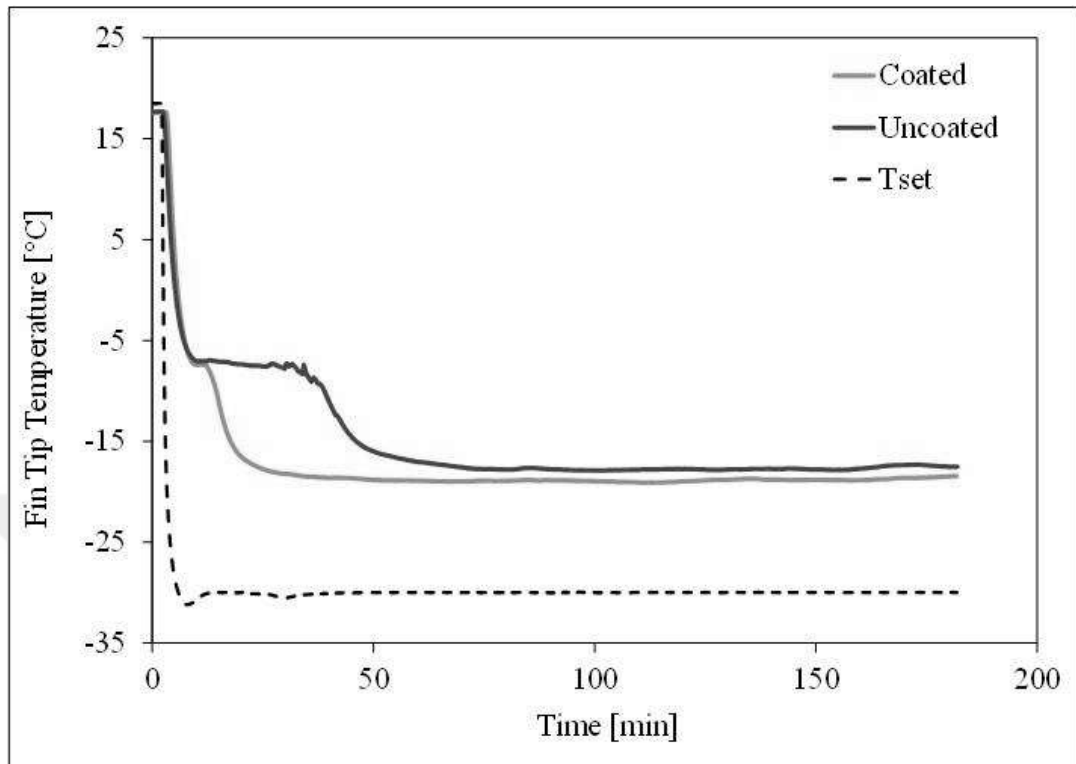


Figure 63. Effect of surface treatment for the set temperature of -30°C and vertical configuration of fins in the experiment C1: Fin tip temperature.

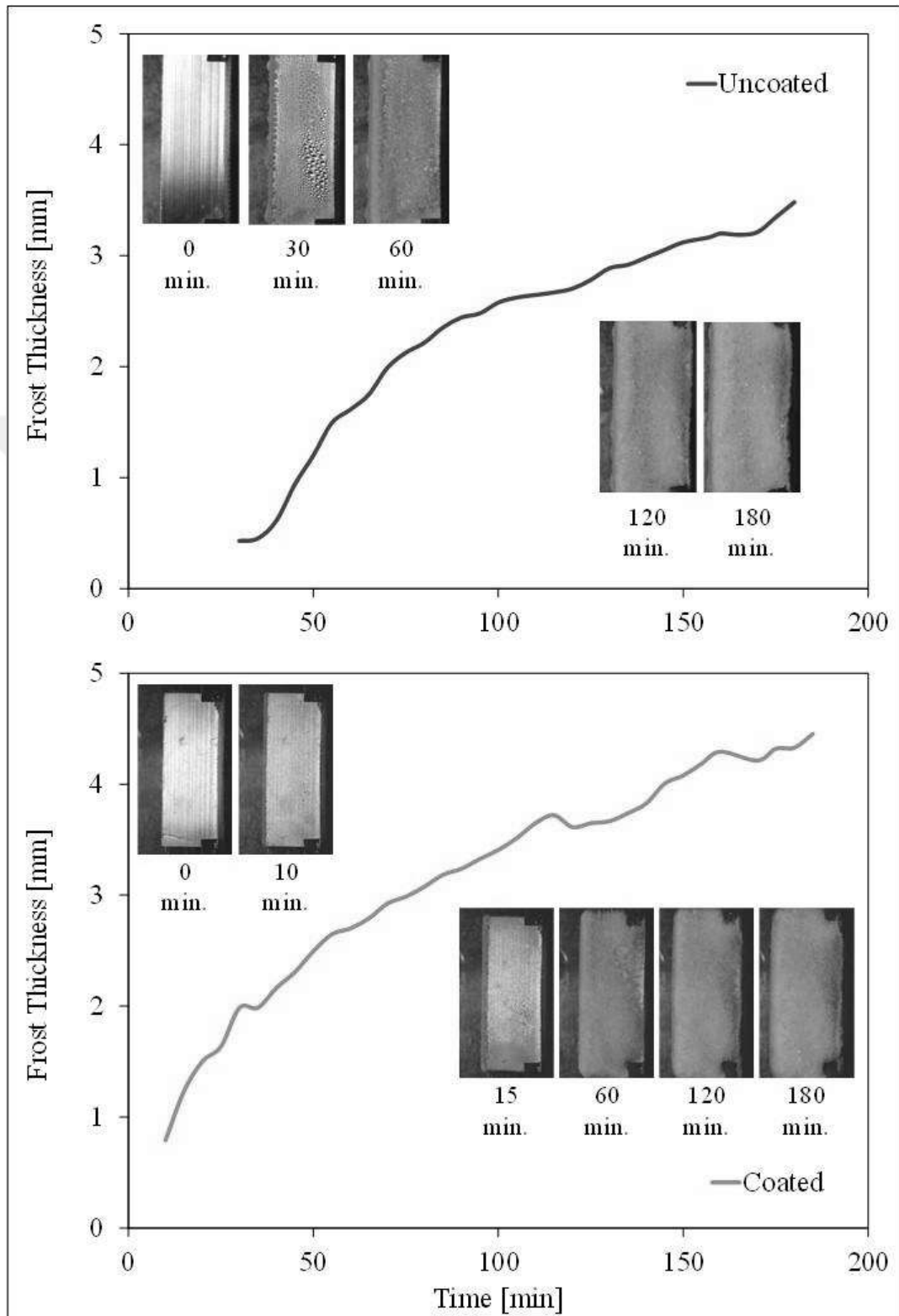


Figure 64. Frost thickness of experiments for C1: a) Uncoated and b) Coated surfaces.

4.7.2 C2 Experiments

In these set of experiments only the air velocity was increased to 2 m/s, but other than that all the conditions were kept as they were in C1. It turns out that the increase in the air velocity had a huge impact on the delay of the frosting with the uncoated surface. As shown in Figure 65, heavy liquid water condensation is present on the uncoated surface. The heavy condensation helps in delaying the frosting process and which preserves a relatively higher heat flow rate through the surface for a longer period of time. Fin tip temperatures and average fin tip thicknesses were shown in Figure 65 and Figure 66. There, the delay in the frosting with the uncoated surface leads to higher fin tip temperatures with the uncoated surfaces and lower average frost thickness at the end of the experiment.

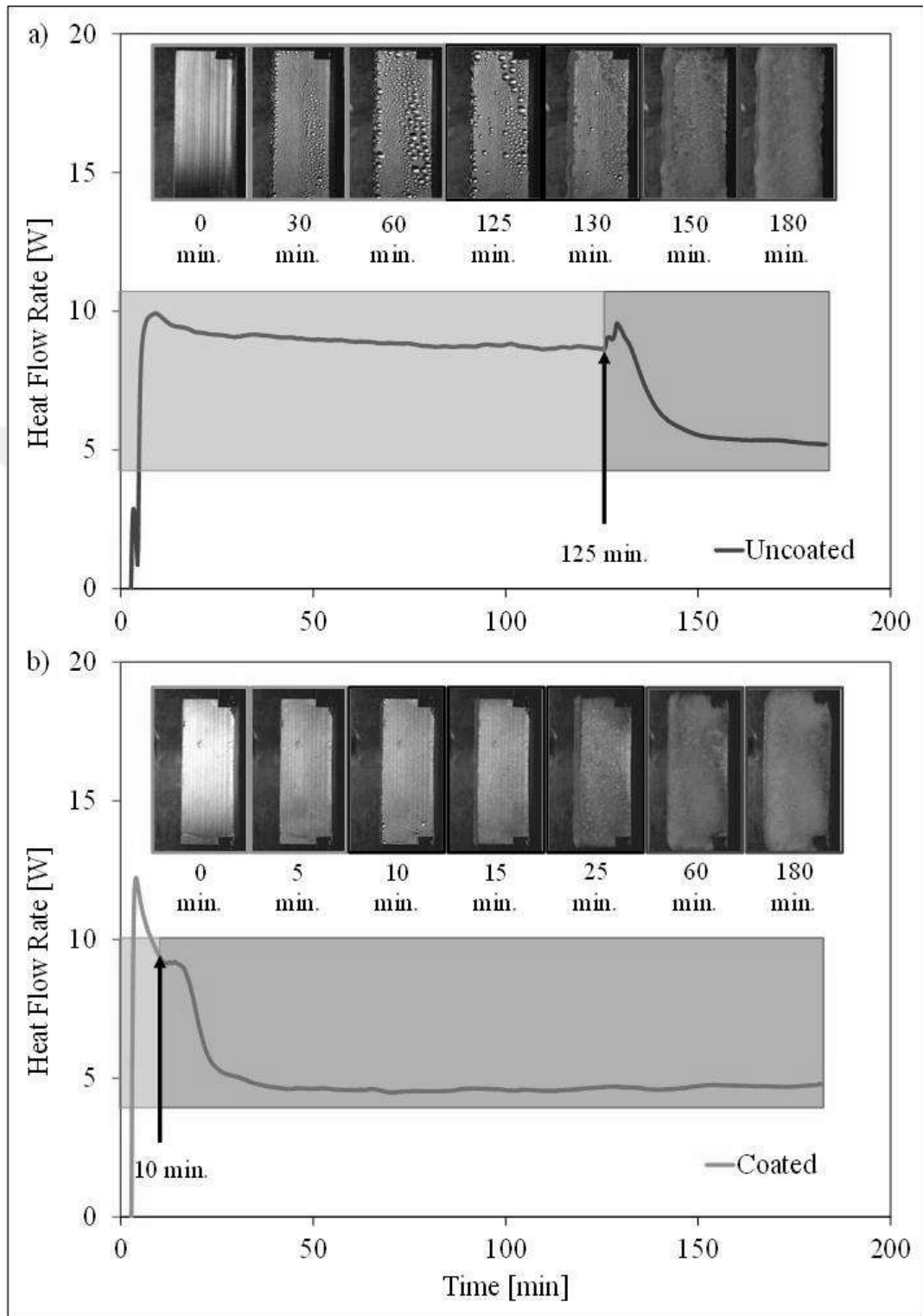


Figure 65. Heat flow rate variations of a) Uncoated and b) Parallel orientations for C2 experiments.

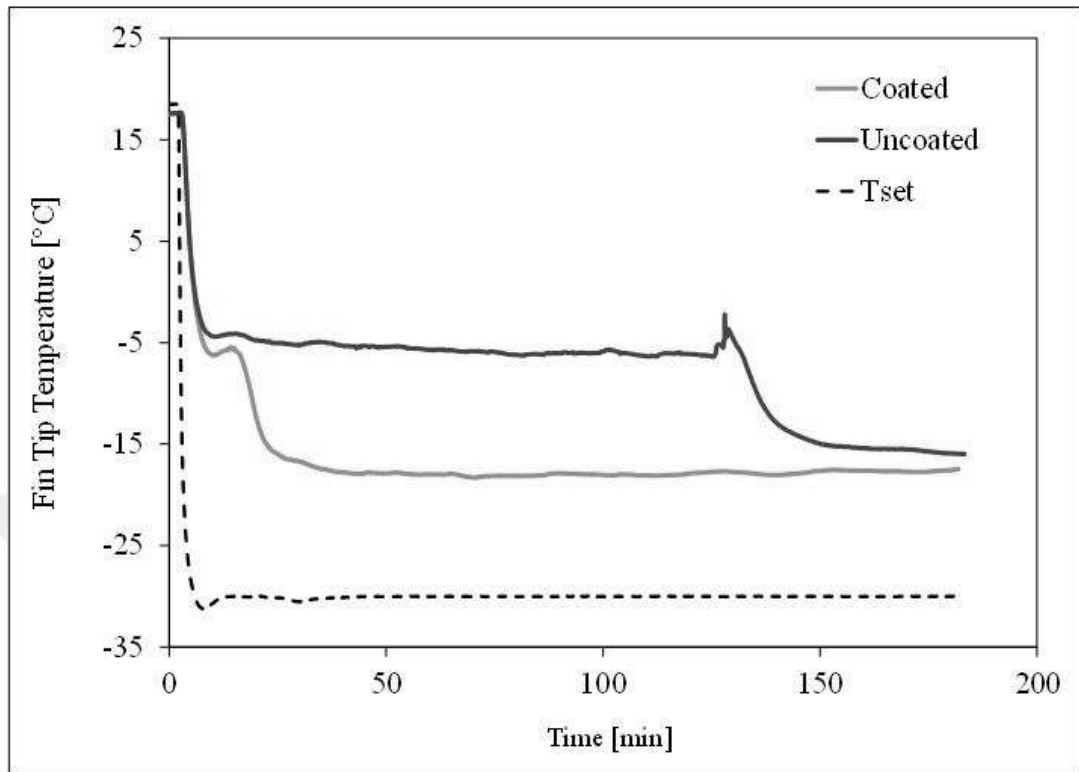


Figure 66. Effects of surface treatment on fin tip temperature in experiment C2.

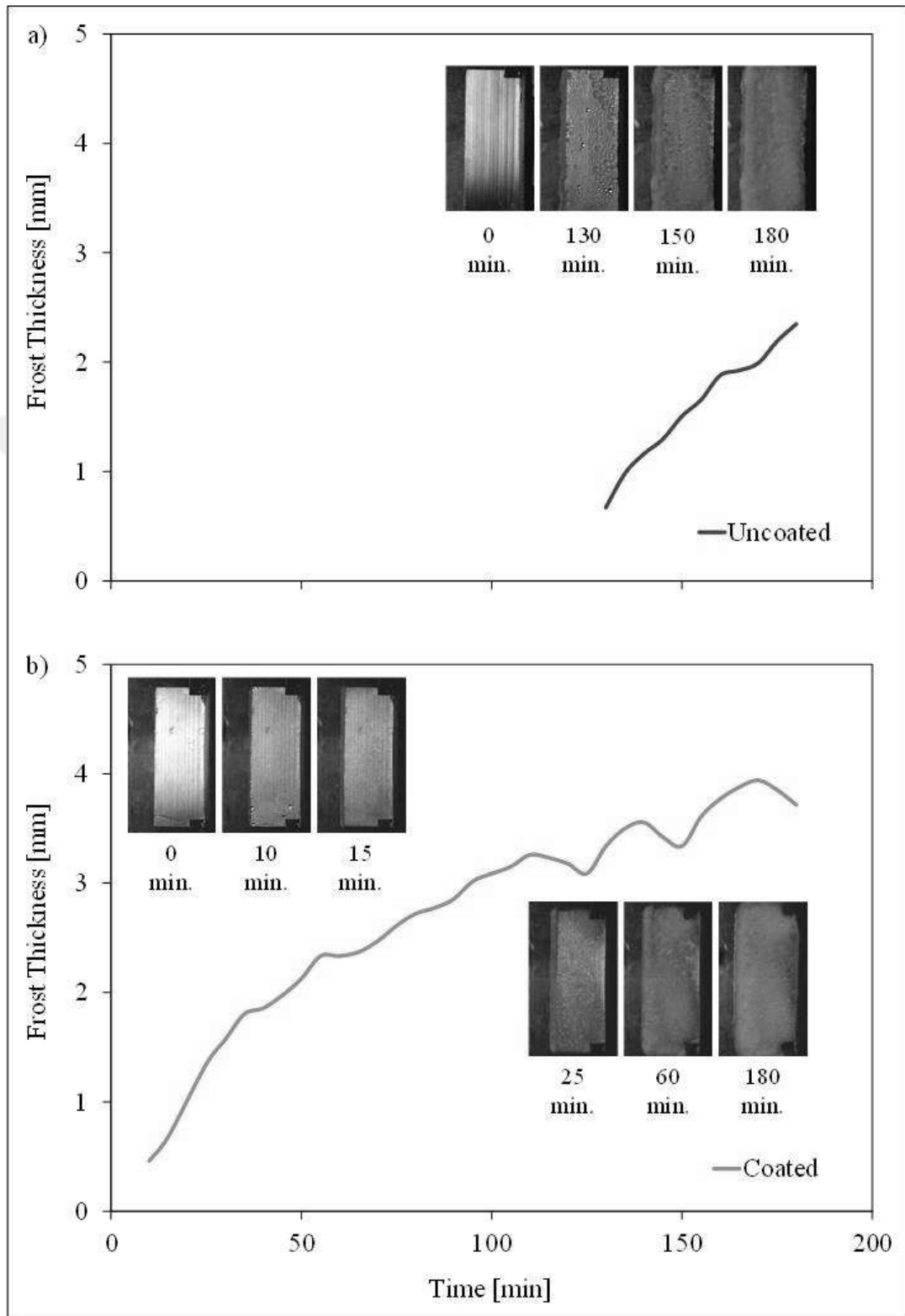


Figure 67. Frost thickness of experiments for C2 a) Uncoated and b) Coated surfaces.

4.7.3 C3 Experiments

In this section the effect of the coating on the heat transfer performance of the finned surface was tested under parallel flow arrangement. Figure 68 shows the heat flow rate through the surfaces. Similar to the previous observations, the drop in the heat flow rate is delayed with the uncoated surface. This is associated with the accumulation of liquid water droplets on uncoated surface. Fin base temperatures shown in Figure 69 are similar to each other. However, at uncoated one the base temperatures are found to be higher due to the delay in the frosting process. Figure 70 shows the average frost thickness on the fin tips. The uncoated one shows a lower average frost thickness compared to the coated one. The difference in the final frost thickness is mostly due to the earlier start of the frosting process at the coated surface.

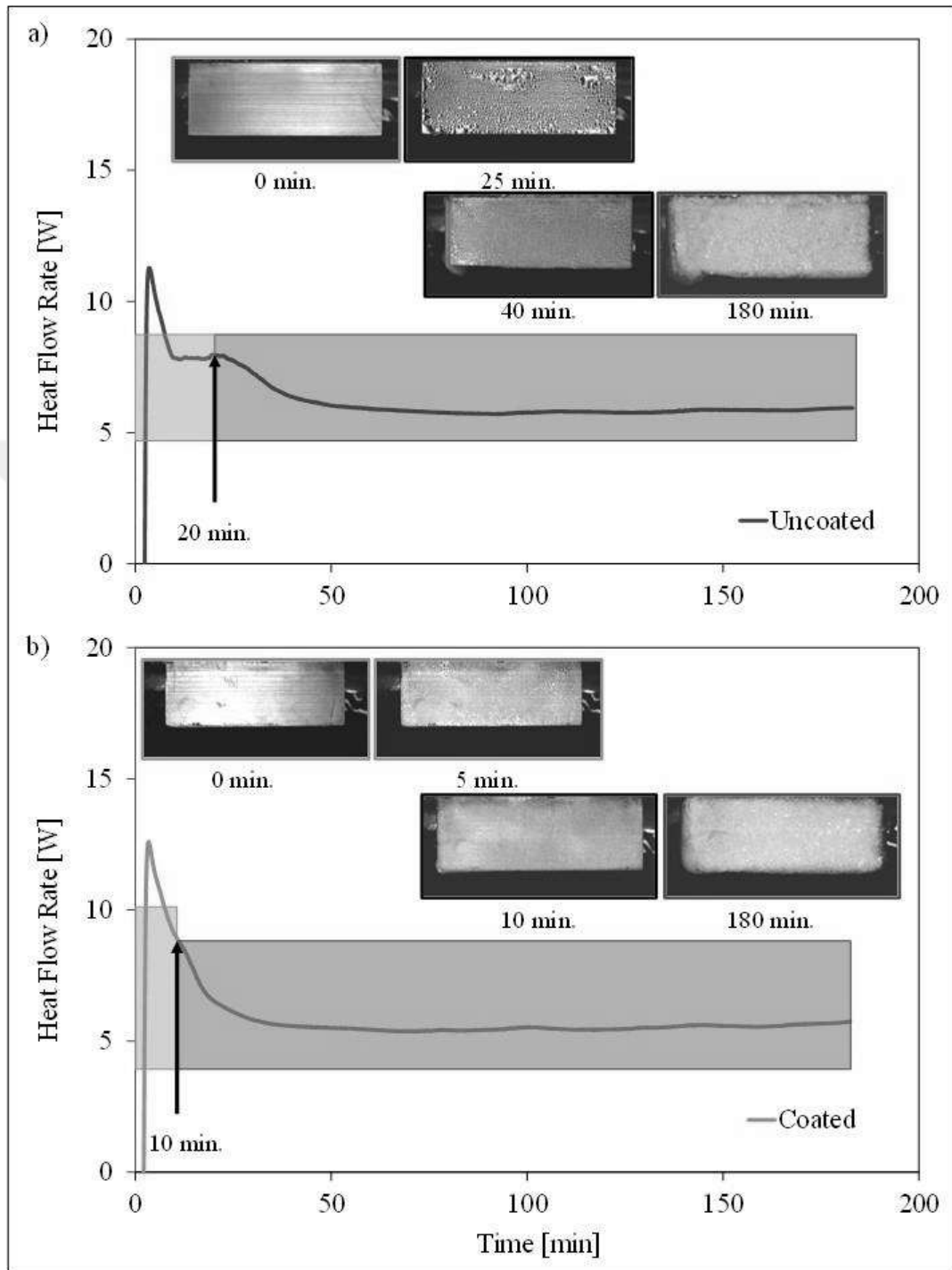


Figure 68. Heat flow rate variations of a) Uncoated and b) Parallel orientations for C3 experiments.

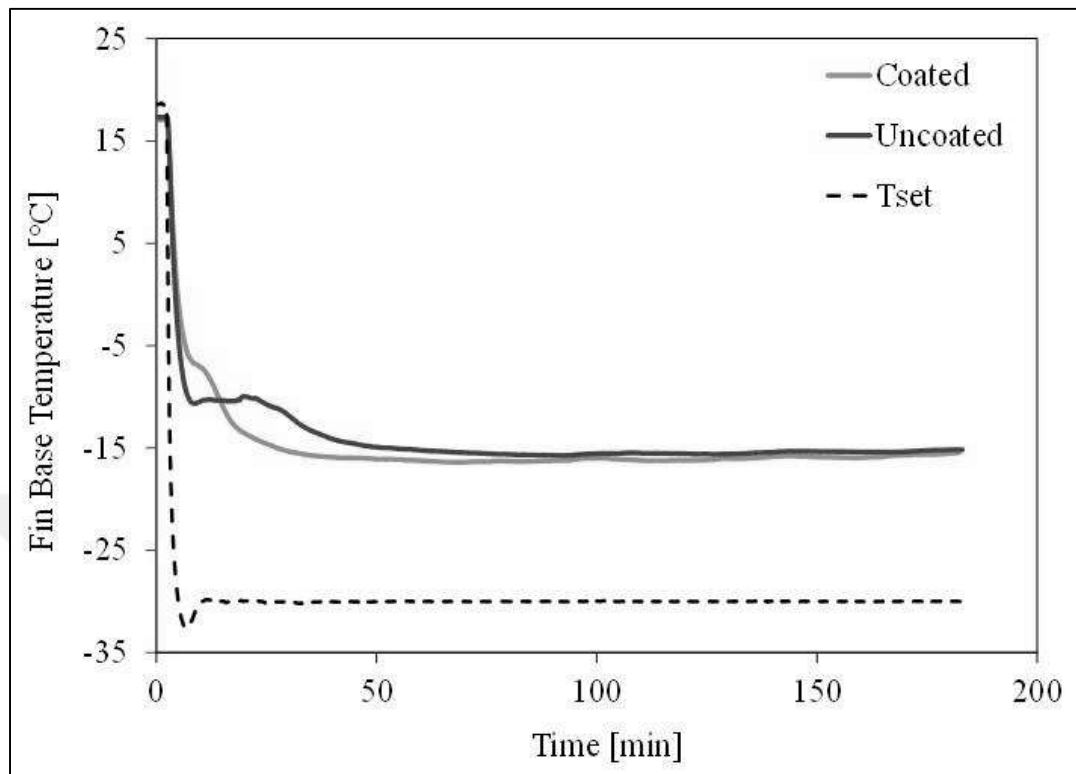


Figure 69. Behaviours of fin tip temperature at surface treatment cases for the set temperature of -30°C .

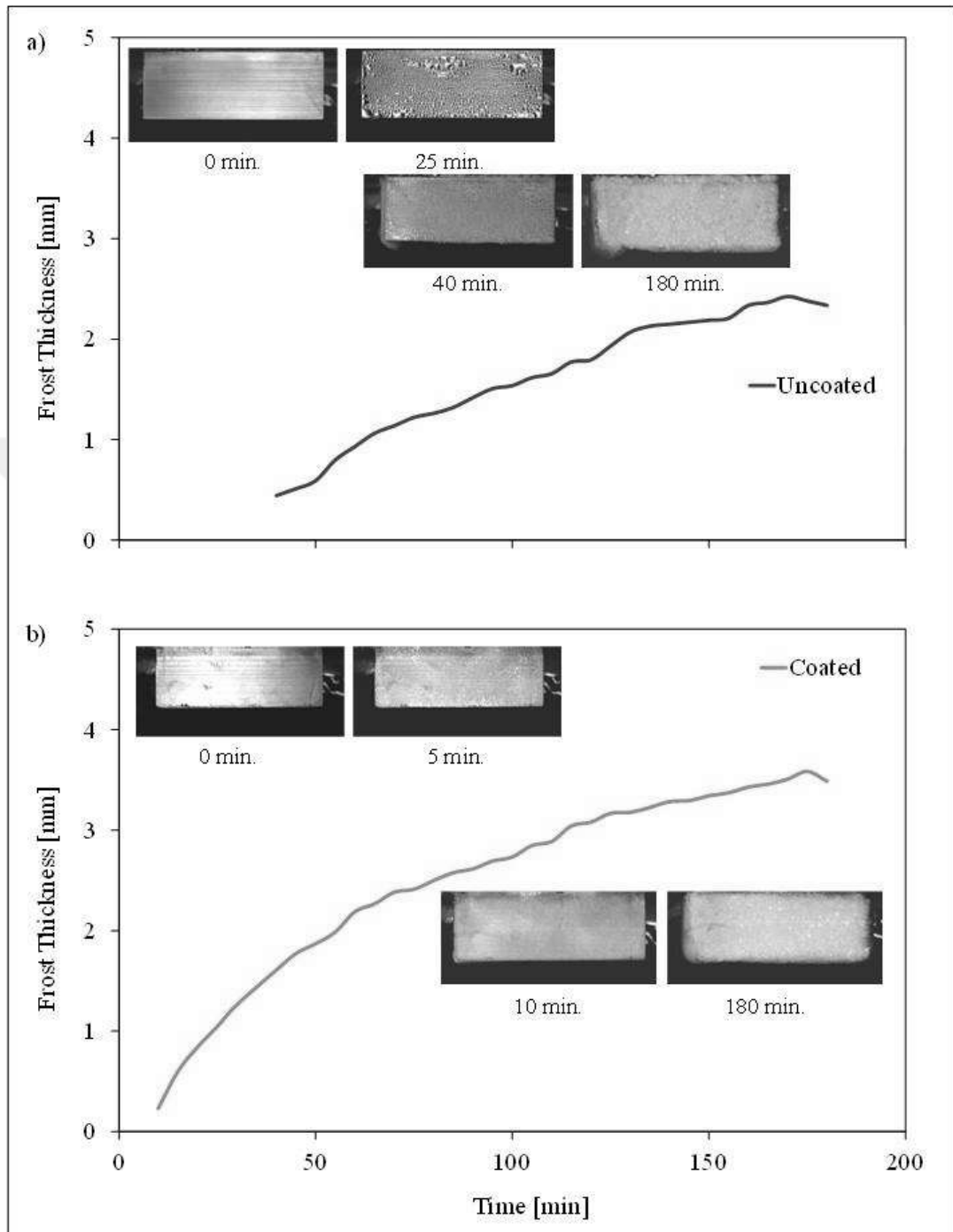


Figure 70. Frost thickness of experiments for C3 a) Uncoated and b) Coated surfaces.

CHAPTER V

SUMMARY AND CONCLUSIONS

Frost formation on flat surfaces generates a barrier for the heat transfer between the air and the surface. However, the effect of frost formation on heat transfer is more severe on finned surfaces. In addition to increasing the thermal resistance between the surface and air frost accumulation on the fins blocks the air penetration in between the fins. Thereby, the effective surface area of the finned surface is heavily reduced and the effectiveness the heat transfer rate between the surface and air drops. In this experimental study the heat transfer performance of finned surfaces was experimentally studied under frosting conditions. In this regard, an open wind-tunnel was designed and manufactured. A temperature controlled finned surface was positioned in the test section of the tunnel. Air at about room conditions is sent through the tunnel. Over time frost formation on the finned surface was observed and meanwhile the heat flow rate through the surface was measured. The effect of different geometrical parameters of the fin such as fin gap, fin length, fin geometry and as well as alignment of the finned surface with respect to air flow on the frosting behaviour of the surface were investigated. Moreover, the effects of superhydrophobic coating, relative humidity of the incoming air, air velocity were also studied in this thesis. The conclusions of this study are summarized below.

1. Regarding the effect of the incoming air relative humidity, it is observed that higher relative humidity delays the frost formation on the surface by resulting in a more pronounced liquid water condensation on the surface. The energy released by the condensation process keeps the fin tips from instant freezing. After a while when the temperature of the water droplets reduces by the heat

transfer, an instant freezing process was observed which also generated a sudden rise in the tip temperature of the finned surface.

2. Regarding the effect of the incoming air velocity, it was found out that the heat transfer rate increases with the incoming air velocity even after complete frost coverage of the surface. The increase in the air velocity also delays the frost initiation on the finned surface which also delays the drop in the heat flow rate due to the blockage of the fin gaps. Increasing the air velocity further than 2 m/s could even eliminate frost formation altogether. It should be kept in mind that in this study the incoming air temperature is above freezing point at 18 °C. Thinner frost thickness was observed for higher air velocity. Some studies [8,13] indicate that the air velocity does not have any influence on the frost thickness or the effect can be negligible [32]. However, in this study showed air velocity promotion causes lower frost thickness. Similarly, Shen and Wang [32] presented in their study that air velocity had a very small effect on frost thickness. However, thinner frost thickness for higher air velocities was observed in this study.
3. The effect of the fin spacing on the heat transfer performance of the finned surface was tested at horizontal alignment of the fins under impinging flow conditions and at parallel alignment of the fins with respect to the incoming air flow. In both alignments of the finned surface, a larger fin spacing is found to result in a delayed drop in the heat flow rate due to the blockage of the air penetration in between the fins. Even though a smaller fin space results in a larger surface area due to the higher number of fins attached to the surface, the susceptibility of the small fin gap to blockage due to the frosting makes the finned surface with small fin gap unsuitable under those conditions.

Liu et al [19] observed higher heat flow reduction for higher fin spaces. Haijie et al [46] indicated, frost formation started earlier on finned surfaces with lower fin gaps than on surfaces with larger fin spaces. However, heat flow rate reduction was lower for higher fin gaps for impinge flow experiments.

4. The effect of the fin length on the heat transfer performance of the finned surface was tested on two different orientations of the surface with respect to the air flow. It has been observed that in both horizontal and parallel orientations of the finned surfaces longer fins increase the heat transfer rate not only due to the increased surface area but also due to the delay in the frost initiation. The surfaces with longer fins were subject to delayed frosting as compared to the surfaces with shorter fins. This combined effect makes the finned surfaces with the longer fins more advantageous compared to the shorter ones.
5. The effect of the fin geometry on the heat transfer rate of the finned surface was also studied. In this study, in addition to the extruded fin type (inline) staggered and knife edge types of fins were considered. The total surface areas of all the finned surface were the same. At 1.5 m/s air velocity and at parallel alignment of the fins no considerable difference in the heat flow rates between the different fin shapes could be found. However, at 2 m/s air velocity and at parallel fin alignment the knife edge shaped fin results in a much higher heat flow rate due to the absence of frosting on the fins. It is not clear why no frost accumulation was found on the knife edge shaped fins. It could be that the convective heat transfer is higher at the fin base due to the better penetration of the air flow in between the fins. However, more detailed studies are required for the exact clarification of this behaviour. In horizontal alignment of the fins and at 1.5 m/s air velocity both staggered and knife edge shaped fins resulted in a higher heat

transfer rate as compared to the inline fin shape. The drop in the heat transfer rate with the knife edge and staggered fin shapes was observed much later than it is with the inline shaped fins.

6. Regarding the effect of the fin orientation on the heat transfer performance experiments were conducted at three different orientations of the inline shaped finned surface. It was observed that the parallel flow arrangement results in the highest heat flow rate whereas the horizontal orientation of the fins resulted in the smallest heat transfer rate.
7. The effect of a superhydrophobic coating on the heat transfer performance of inline shaped finned surface was studied. In this study, the coated finned surfaces both at vertical alignment and parallel flow arrangement were subject to much lower rate of water condensation on the surface. The superhydrophobic surface prevented the adhesion of the condensed water droplets on the finned surface which resulted in an earlier frost growth. Air velocity increasing did not show important effects on heat transfer rate delay for coated surface. However, the heat flow rate decrease of the uncoated surfaces was delayed much later than the coated surface due to the increase of condensed water droplets. The coated surface also resulted in an earlier drop in the heat flow rate due to the blockage of the fin gaps. Peaks were not observed on the coated surfaces since large water droplets did not occur. Overall, one can say the superhydrophobic surface worsened the heat transfer performance of the surface both at impinging flow and parallel flow arrangements. This results compromise with study of Sommers et al [25].

This study shows different configurations of surface and environmental conditions. Most of results proves outcomes of earlier studies but still there is not a consensus

about air velocity effect on frost formation. Higher air velocities increased condensation of water vapor droplets and it delayed the heat flow rate drop. Recent studies like Song et al [43] focus on freezing process of the droplets to understand effects of droplets on frosting. In this study proved dominant effects of condensed water droplets on frosting process. However, effects of condensed water droplets in frost formation process should be investigated more deeply.



CHAPTER VI

RECOMMENDATIONS FOR FUTURE WORK

In this study, frost formation on the finned surfaces under impinging flow conditions was investigated for different air velocities, relative humidity, fin lengths, fin spaces, fin types, surface orientations and surface treatment. Experiments have been investigated for heat transfer rate, frost thickness, fin effectiveness variations. These investigations are not enough to understand the structure of frost and the peak of temperatures. Results showed condensed water droplets on the surfaces are very important for frost formation. Experiments and older studies showed that condensed water droplets are the main reason for the peak points. In future studies, condensation on a cold surface and the droplets icing process can be investigated more deeply. Also, the size and amounts of condensed water droplets should be studied to understand the effects on heat transfer rate, frost density and thermal conductivity, since these parameters are very important for cooling system energy consumption. Because of that, condensation effects on frost formation can be investigated for an actual cooling system in detail. Moreover, for an optimized system, energy consumption can be the best parameter to be satisfied. On the other hand, the entrained air between branches of frost is one of the biggest reasons for low effective thermal conductivity. Although, a special interest was given for all parameters in the current study, different structure of those branches can be another step to focus on the next study. Another, point to be enlarged can be that any peak point and heat flow rate reduction were now observed at flat plate experiments in the current study due to that the frost covered all the surface. That means the high thermal resistance of frost already occurred and thickness increase does not affect thermal resistance significantly. Thus, to be able to capture this effect to, constant

heat flow rate settlement and temperature variation observations can be very important studies for flat plate experiments.



APPENDIX

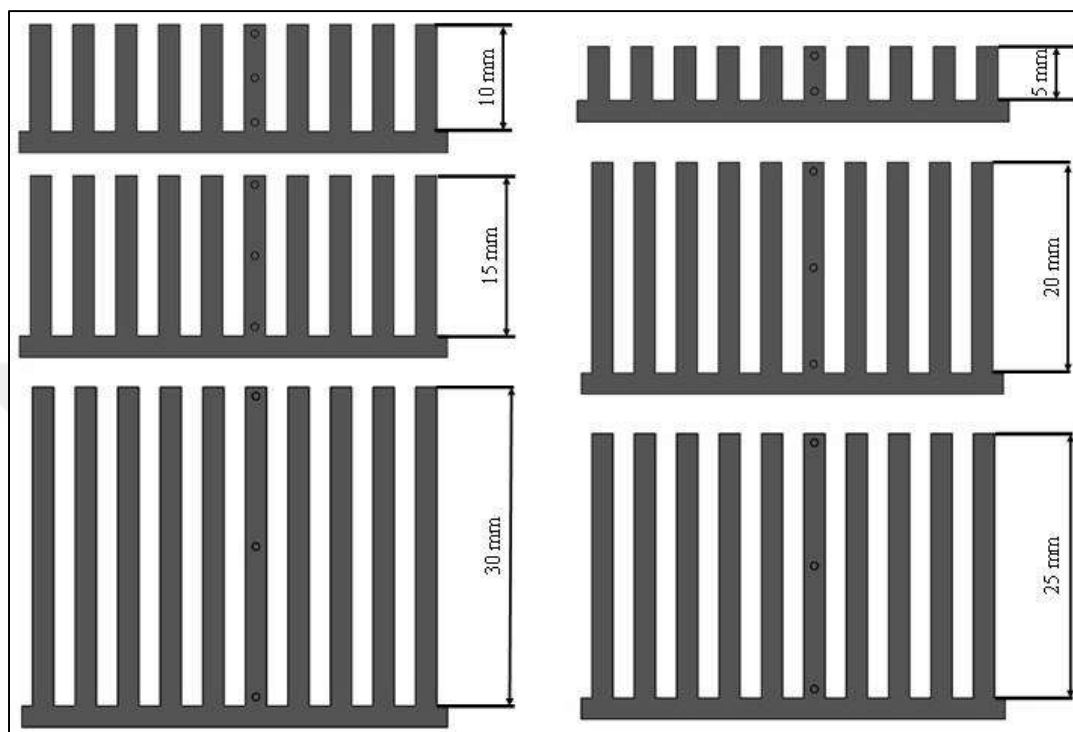


Figure A-1. Images of different fin lengths with 2 mm fin spaces.

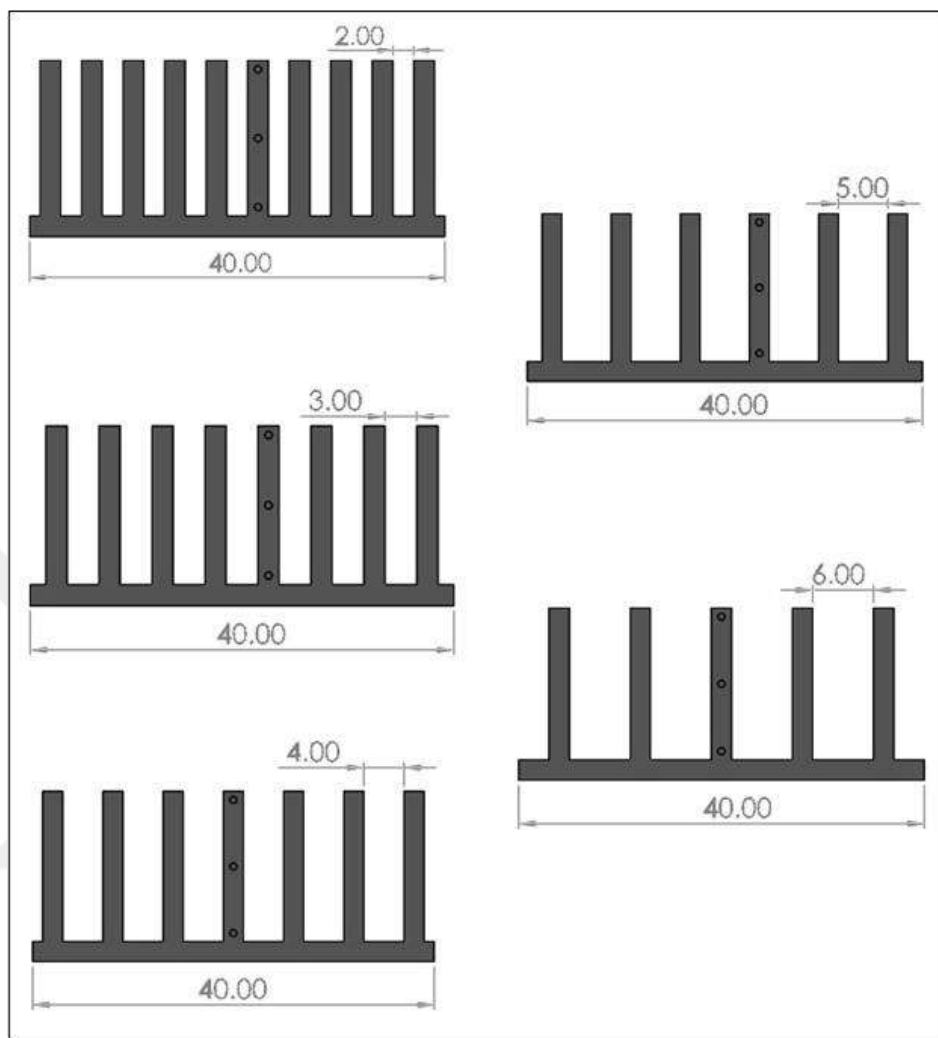


Figure A-2. Images of different fin spaces with 15 mm fin length.

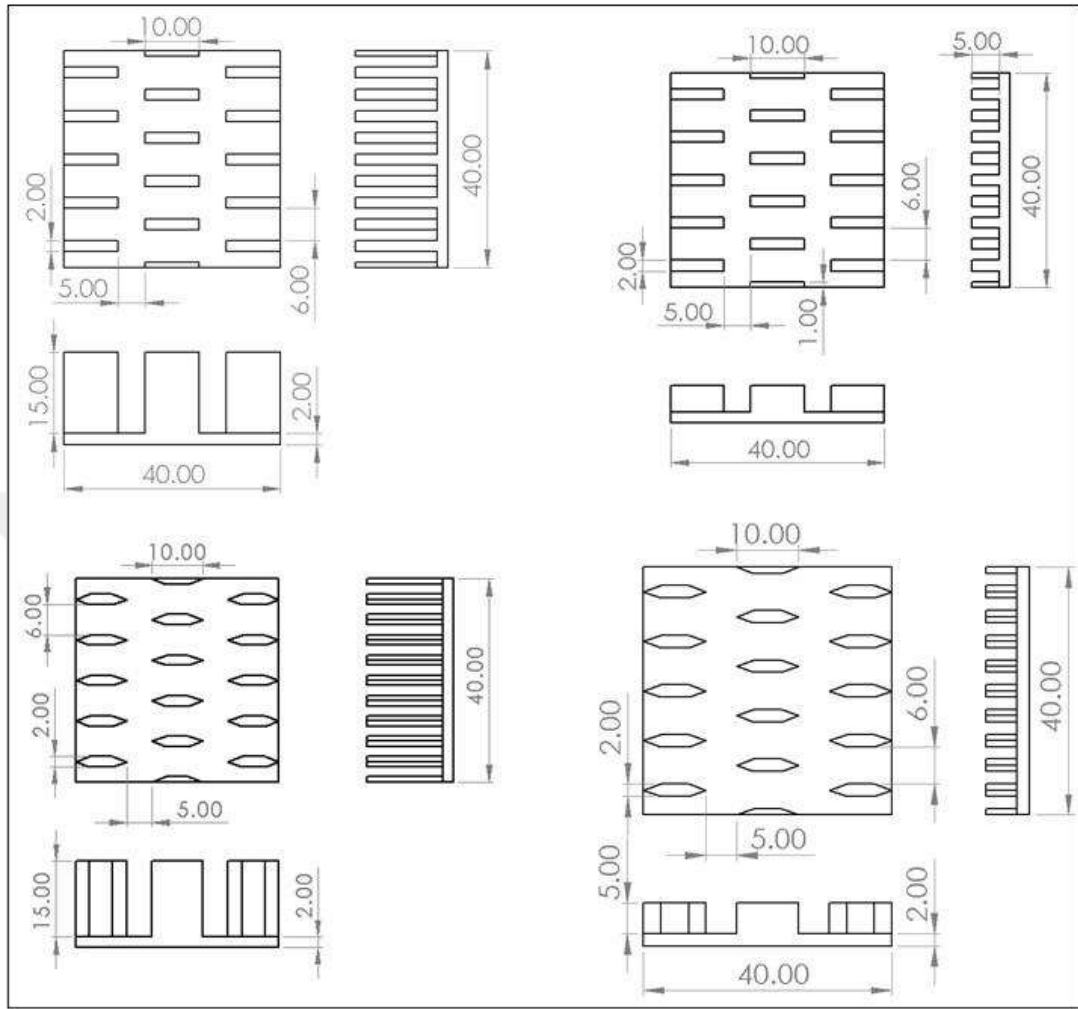


Figure A-3. Technical drawing of different fin types.

Experiment Code	Variable	Heat Transfer Rate Uncertainty		Fin Effectiveness Uncertainty	
		Minimum	Maximum	Minimum	Maximum
RH1	40%	± 5.94	± 10.77	-	-
	55%	± 5.94	± 9.69	-	-
RH2	40%	± 5.18	± 8.96	-	-
	55%	± 4.51	± 8.87	-	-
	65%	± 4.26	± 8.11	-	-
V1	1.5 m/s	± 5.08	± 8.66	-	-
	2 m/s	± 4.64	± 7.9	-	-
	2.5 m/s	± 4.44	± 7.2	-	-
V2	1.5 m/s	± 4.51	± 8.87	-	-
	2 m/s	± 4.73	± 8.31	-	-
	2.5 m/s	± 4.47	± 7.4	-	-
	3 m/s	± 4.32	± 7.06	-	-
V3	1.5 m/s	± 6.23	± 7.13	-	-
	2 m/s	± 4.82	± 8.53	-	-
	2.5 m/s	± 4.51	± 7.73	-	-
S1	2 mm	± 4.51	± 8.87	-	-
	3 mm	± 4.79	± 7.39	-	-
	4 mm	± 5.15	± 8.48	-	-
	5 mm	± 5.35	± 8.57	-	-
	6 mm	± 5.8	± 9.44	-	-
S2	2 mm	± 5.54	± 7	-	-
	5 mm	± 5.1	± 7.36	-	-
	6 mm	± 5.49	± 7.14	-	-
L1	5 mm	± 10.85	± 14.59	± 11.77	± 13.42
	10 mm	± 7.75	± 12.19	± 13.07	± 19.64
	15 mm	± 5.94	± 10.77	± 14.25	± 22.74
	20 mm	± 6.52	± 9.36	± 18.3	± 24.37
	25 mm	± 5.68	± 7.78	± 21.77	± 29
	30 mm	± 5.41	± 6.94	± 28.42	± 31
L2	5 mm	± 8.69	± 12.14	± 7.72	± 9.48
	10 mm	± 6.14	± 10.38	± 8.41	± 13.39
	15 mm	± 5.18	± 8.96	± 8.74	± 15.93
	20 mm	± 5.06	± 7.89	± 10.42	± 17.8
	25 mm	± 4.56	± 6.88	± 11.95	± 20
	30 mm	± 4.29	± 6.18	± 22.65	± 31
L3	5 mm	± 7.98	± 8.13	-	-
	15 mm	± 5.54	± 7	-	-
FT1	Inline	± 5.49	± 7.14	-	-
	Staggered	± 5.19	± 7.31	-	-
	Knife Edge	± 5.1	± 7.26	-	-
FT2	Inline	± 5.1	± 6.33	-	-
	Staggered	± 4.56	± 6	-	-
	Knife Edge	± 4.24	± 4.43	-	-
FT3	Inline	± 5.8	± 9.44	-	-
	Staggered	± 4.99	± 7.15	-	-
	Knife Edge	± 5.29	± 6.91	-	-
A1	Vertical	± 5.08	± 8.66	-	-
	Horizontal	± 4.51	± 8.87	-	-
	Parallel	± 5.54	± 7	-	-
C1	Coated	± 4.41	± 8.97	-	-
	Uncoated	± 5.08	± 8.66	-	-
C2	Coated	± 4.82	± 8.53	-	-
	Uncoated	± 4.64	± 7.9	-	-
C3	Coated	± 4.92	± 7.22	-	-
	Uncoated	± 5.54	± 7	-	-

Figure A-4. Uncertainty values of experiments.

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