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Experimental investigation of condensation heat transfer on vertically inclined grooved aluminium surfaces

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Abstract. This study details the experimental investigation of surface condensation heat transfer on vertically inclined aluminium surfaces with simple modifications. A bespoke experimental apparatus was constructed to control the saturation conditions inside the condensation chamber where the test surface is located. The degree of subcooling of the test surface was precisely controlled by an external heat exchanger. The meter bar technique was used to evaluate the condensation heat flux. Using distilled water as the working fluid and a plane aluminium test surface as the baseline case, the experimental apparatus was validated by comparison of the determined heat transfer coefficient with Nusselt's model of filmwise condensation on a vertical plane surface, where an excellent agreement was obtained. 7 different aluminium test surfaces were subsequently investigated, each one modified with grooves measuring 0.5mm by 0.5mm (height and width), with a consistent spacing of 0.5mm between them. Groove angles relative to the vertical axis of 0° (180°), 30°, 45°, 60°, 90°, 120°, and 150° were investigated, where grooves were symmetrically mirrored at the centre of each test surface. Results highlighted a significant influence of groove angle on the heat transfer coefficient, with the best-performing sample (150˚) producing a maximum enhancement of 45% and an average enhancement of 34% compared to the baseline test surface over the respective range of subcooling.

1. Introduction

Surface condensation is a phase change process where vapor or gas cools and becomes a liquid upon contacting a surface whose temperature is below the saturation temperature of the fluid. Condensation of the working fluid releases substantial latent heat; hence this phenomenon is critical in a wide range of industrial applications, including HVAC systems, chemical processing, refrigeration, and power generation, notably in thermal and nuclear power plants. Comprehending, controlling, and optimizing this process is essential for designing more efficient and more compact heat exchangers, enhancing the rate of condensation heat transfer, and reducing energy use and associated costs. Moreover, in the realm of electronics cooling, surface condensation is increasingly crucial to the operation of vapor chambers and heat pipes. As electronic devices become more compact and power-dense, high-efficiency cooling is necessary to avoid overheating and maintain functionality.

This study primarily aims to explore if simple modifications, such as adding easily machinable grooves to the condensation surface, can enhance heat transfer efficiency, and if so, by how much. The specific objectives are (i) to validate the experimental apparatus by comparison of results with established filmwise surface condensation theory, and (ii) to assess how various inclinations and patterns of machined grooves on the surface impact the condensation heat transfer.

There are several studies that investigate if micro-grooved surfaces can enhance condensation heat transfer. Qi et al. [1] studied sine-shaped micro-grooved surfaces with a depth of 12–24μm and width of 30–60μm created on aluminium surfaces by dry etching. During dropwise condensation for vertically aligned grooves, the cleaning effects of falling droplets were enhanced and the associated heat transfer was increased by up to 50%, whereas horizontally aligned grooved surfaces produced results similar to that of a smooth surface. Conversely, Budalki et al. [2] found little, if any, improvement in heat transfer performance during dropwise condensation on their copper surfaces modified with square and V-shaped grooves of height 500μm and pitch 500μm to 1000μm, when compared with an unmodified surface. Budalki et al. [3] later found that although square grooves provided a 50% increase in condensation surface area, the thermal performance reduced by almost 30% compared to the unmodified surface. Davar et al. [4] experimentally investigated condensation heat transfer on six hydrophilic aluminium plates with different surface morphologies created by nanosecond fibre laser. The process resulted in surface roughness in the form of cavities with mean diameter of 50μm and depth of 5μm. The authors concluded that a delicate balance between increased surface area, roughness, and convenient paths for the flow of condensate; increased area was found to promote heat transfer, but increased roughness inhibited the removal of condensate.

2. Experimental method

Figure 1 shows an annotated image of the bespoke experimental apparatus designed to investigate and measure condensation heat transfer on vertically inclined aluminium surfaces.

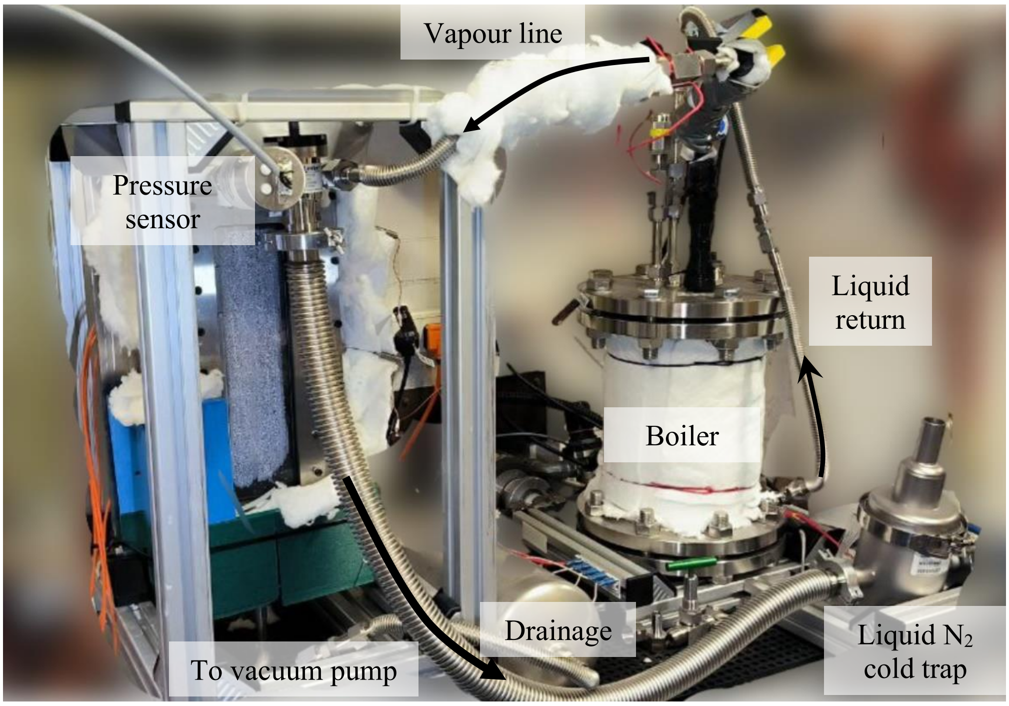
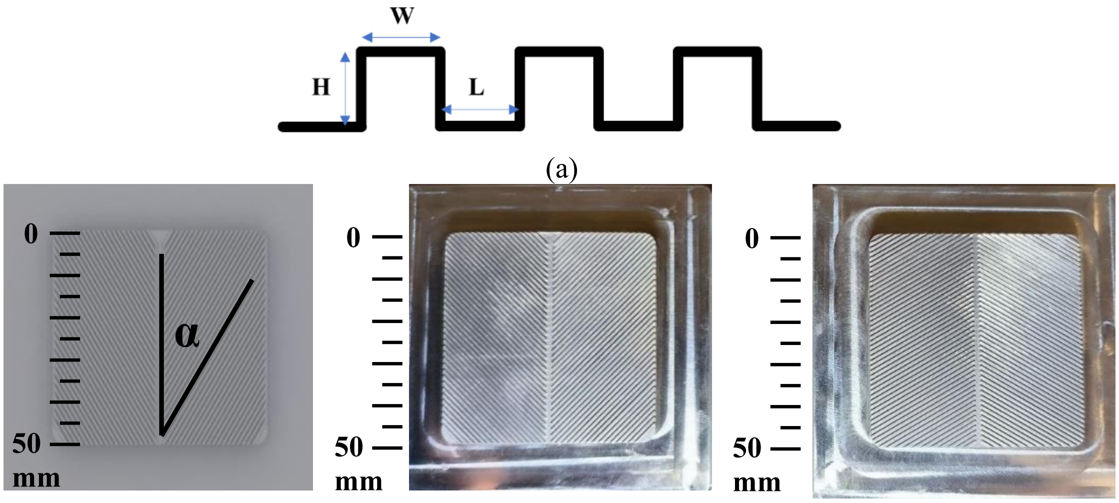


Figure 1. Photo of the experimental rig. Various pieces of thermal insulation have been removed.

Distilled water vapour is generated within the boiler, a 152mm diameter, 300mm height, 316-grade stainless steel vessel in which four 16mm diameter, 150mm long Thermelec cartridge heaters with a rated power of 1kW are immersed. The vapour and liquid temperatures inside the boiler are monitored using calibrated 1mm diameter type-K thermocouple probes connected to a National Instruments (NI) NI-9214 data acquisition module (DAQ). The vapour produced in the boiler is transported through a stainless-steel vapour line into the condensation chamber. This chamber, with internal dimensions measuring 180mm in width, 480mm in height, and 50mm in depth, serves as a controlled environment for surface condensation. Vapour enters the condensation chamber from the top. A MKS 728A13TCE2FB pressure transducer monitors the chamber pressure, its readings recorded by a NI-9201 DAQ. The chamber is connected to a Varian EXSH01001UNIV vacuum pump in line with a Kurt J. Lesker TLR4X100QF liquid nitrogen cold trap to ensure the non-condensable gases are removed and to assist in setting the system pressure. A viewing window, made from clear polycarbonate, forms part of the front surface of the chamber. There is a cutout in the back wall of the chamber to allow for the insertion and replacement of various condenser test surfaces. Gravity causes condensate to leave the chamber at its bottom, where a drainage vessel captures it and if needed, returns it to the boiler with the help of a pump. The condensation chamber temperature is continuously monitored by three calibrated 1mm diameter type-K thermocouple probes connected to the NI-9214. These are strategically positioned along the chamber's length from top to bottom to provide a comprehensive temperature profile.

The condensation test surface area is 50mm x 50mm. The condenser samples, an example of which is shown in Figure 2, are manufactured from aluminium (grade 6082). One smooth condensation surface is used as a baseline case. The remaining condensation surfaces are engineered with grooves to enhance the condensation efficiency and study the impact of groove orientation. The grooves have a height (H) and width (L) of 0.5mm, with a consistent spacing (L) of 0.5mm between them (see Figure 2(a)). Each grooved surface has grooves at a different angle (α). In total, 7 grooved samples are investigated: α = 0° (180°), 30°, 45°, 60°, 90°, 120°, and 150° where α is measured relative to the vertical axis and grooves are symmetrically mirrored at the centre of each test surface, as shown in Figure 2(b) for a groove angle of 60°.



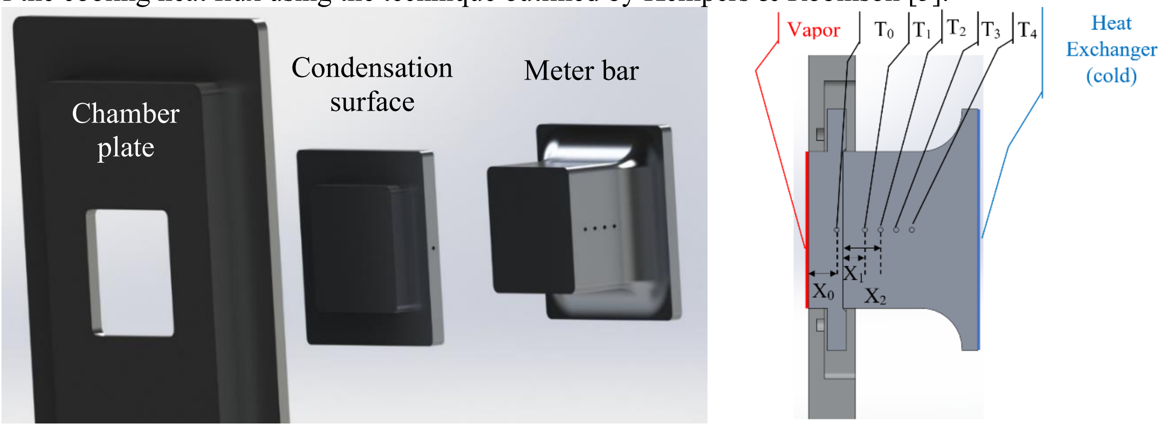
(a)

(b) (c) (d)

Figure 2. (a) Schematic of grooves applied to the condensing surfaces, (b) sample condenser surface showing $\alpha = 30°$, (c, d) photos of test surfaces with $\alpha = 45°$, and $120°$ respectively.

As shown in Figure 3, the back side of the condenser surface under test is in contact with an aluminium meter bar. This meter bar is an integral part of a cooling system and is connected at one end to a copper heat exchanger equipped with interior rectangular channels. Distilled water is circulated through the copper heat exchanger by a ThermoFisher Polar Series Accel 500 LC recirculating chiller. Its volumetric flow rate is measured using a RS 511-4772 rotameter and the water temperature at the inlet and outlet of the heat exchanger is measured by two stainless-steel probe 1.5mm diameter type-T thermocouples. This setup ensures the effective dissipation of heat from the condenser test surface.

Four holes are strategically drilled in the meter bar to house 1.5mm diameter four-wire resistance temperature detectors (RTDs) which are connected to a NI-9216 DAQ, enabling precise measurement of the cooling heat flux using the technique outlined by Kempers & Robinson [5].



(a) (b)

Figure 3. (a) Exploded view of one wall of the stainless-steel condensation chamber, aluminium test surface, (b) aluminium meter bar, showing the thermocouple locations.

To assess the effectiveness of the condensation heat transfer, we calculate the condensation heat flux (q'') and the subcooling temperature (ΔT_{sub}) to compute the heat transfer coefficient (h_{cond}):

$$h_{cond} = \frac{q''}{\Delta T_{sub}} \tag{1}$$

Subcooling is determined by the temperature differential between the vapor and the test surface, with vapor temperature being derived from the pressure sensor data and the known saturation temperature dependence on pressure [6]. The surface temperature is ascertained using the Heated Meter Bar Technique (HMBT), which is a well-established method in the heat transfer community, comprehensively detailed in Ref. [5] and effectively used in Ref. [7]. In measuring the heat flux to the exposed surface as shown by equation (2), a simple determination of the temperature gradient (dT/dx), coupled with an accurate understanding of the meter bar's thermal conductivity (k_{MB}), is adequate for one-dimensional heat flow analysis:

$$q'' = -k_{MB}\frac{dT}{dx} \tag{2}$$

The temperature gradient is calculated via a least-squares linear regression fit applied to the measured data on the temperature vs. distance graph for meter bar thermocouples 1-4. Subsequently, the surface temperature as given by equation (3) can be indirectly gauged by extrapolating the T_0 vs. x curve to the interface of the condensing surface:

$$T_s = T_0 - \left|\frac{dT}{dx}\right|(x_0) \tag{3}$$

3. Results and Discussion

The experimental rig, procedure, and reproducibility of results are first validated by comparison with Nusselt's model for filmwise condensation on a vertical plane surface [8]. For this comparison, the baseline condensation surface was used. Figure 4 shows excellent agreement (within the measurement uncertainty ± 1kW/m^{2}K) over the range of sub-cooling temperatures $1.4\text{K} \leq \Delta T_{sub} \leq 13\text{K}$. Also in the figure are the results for each of the modified, grooved samples, on which filmwise condensation was the observed mode. Evidently, the groove angle has a significant effect on the condensation surface heat transfer coefficient (h_{cond}). The presence of grooves on the surface introduces a capillary action that draws fluid into the grooves, effectively clearing the topmost surfaces and enabling the liquid to drain away. This capillary action, however, has a downside. It retains a certain amount of liquid at the bottom of each groove, and this retained liquid's height is determined by the groove's dimensions and physical properties of the fluid. This results in a system where the condensate thickness is not particularly affected by subcooling, unlike what is observed with flat surfaces, which in turn diminishes the influence of subcooling on h_{cond}.

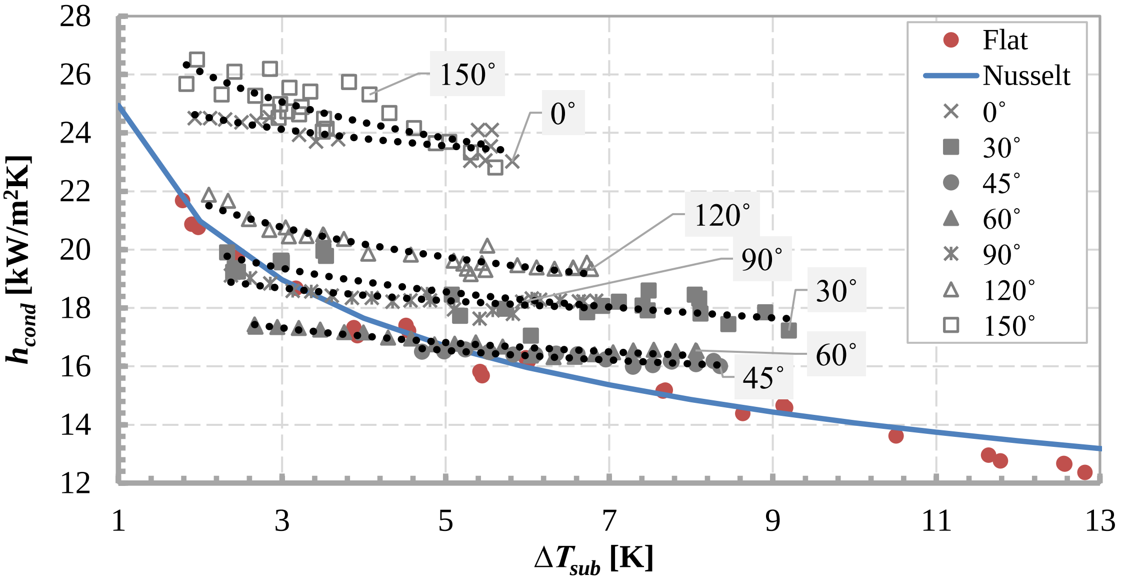


Figure 4. Filmwise condensation heat transfer coefficient versus subcooling for the smooth (baseline) and grooved aluminium surfaces at varying groove angles.

All samples show a reduction in heat transfer with increasing subcooling, as expected due to the flooding of grooves. The sample with groove angles of 45° performed better than the smooth surface, but this sample performed worst of all grooved samples, showing little effect of subcooling on h_{cond}. Similar performance was observed for groove angles of 60°, with a modest improvement for groove angles of 30° and 90°. Above an angle of 90°, the grooves direct condensed fluid away from the centre of the test surface, and a marked increase in performance is observed, with the largest improvement noted for groove angle of 150°, which somewhat surprisingly outperforms the 0° (=180°) sample.

Figure 5 shows that the trend of the heat transfer coefficient vs. groove angle is quite repeatable over the narrow range of low subcooling 3K $\leq \Delta T_{sub} \leq$ 5K.

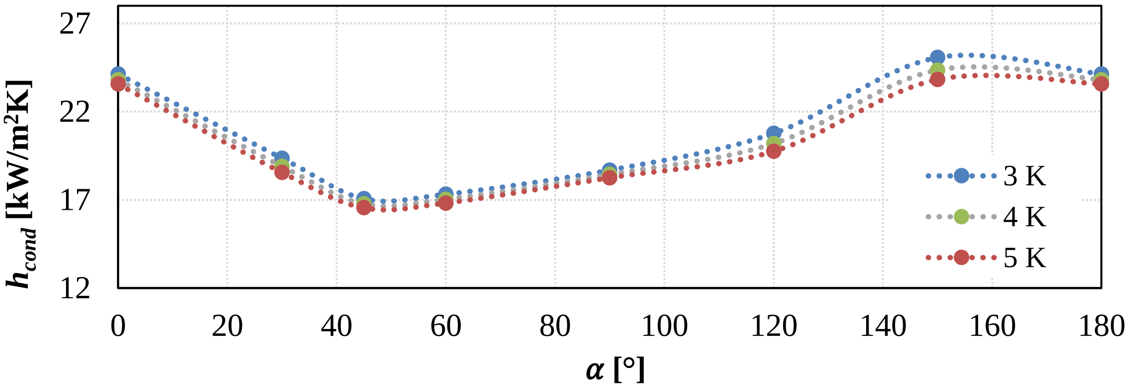


Figure 5. Condensation heat transfer coefficient versus groove inclination angle for subcooling temperatures of 3 K to 5 K.

4. Conclusion

This research presents an experimental study of condensation heat transfer on aluminium vertical surfaces and investigates if simple surface modifications can lead to significant enhancements in surface heat flux. A bespoke experimental setup was developed and rigorously validated against Nusselt's model for filmwise condensation. The experiment reliably controlled the saturation conditions for surface condensation and allowed for precise measurement of the condensation heat flux. 8 grooved test surfaces, each with surface features of similar dimension but at different angles, were investigated and compared to a baseline case. The grooved modifications to the test surfaces, with variable angles relative to the vertical axis, demonstrated a marked impact on the heat transfer coefficient. Notably, the sample with grooves at 150° angle exhibited a maximum increase of 45% and an average increase of 34% in heat transfer efficiency over the unmodified surface, underscoring the potential of such simple geometric alterations to significantly improve condensation heat transfer in practical applications.

Moreover, an interesting trend was noted across all surfaces, where heat transfer enhancement intensified with increased subcooling, likely due to improved capillary-driven drainage in the grooves. Contrary to expectations, the poorest performance emerged not from the horizontally oriented grooves ($\alpha = 90°$) but from those set at a 45° angle.

This investigation not only affirms the viability of machined micro-grooves as a method to augment condensation heat transfer but also sets a foundation for further research. Future studies may explore the integration of these micro-groove patterns into larger-scale industrial condensers, the impact of different fluids and flow conditions, and the long-term durability and maintenance of such structured surfaces. The continuation of this work could lead to significant strides in thermal management technologies, ultimately contributing to global efforts in energy conservation and sustainability.

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