Journal of Physics: Conference Series

PAPER • OPEN ACCESS

A new test section made via additive manufacturing to perform local heat flux measurements

To cite this article: G Cattelan *et al* 2024 *J. Phys.: Conf. Ser.* **2766** 012171

Journal of Physics: Conference Series **2766** (2024) 012171 doi:10.1088/1742-6596/2766/1/012171

A new test section made via additive manufacturing to perform local heat flux measurements

G Cattelan[1], M Azzolin[1], S Bortolin[1], M Bonesso[2], A Pepato[2] and D Del Col[1]

[1] University of Padova, Department of Industrial Engineering
Via Venezia 1, 35131 – Padova, Italy
[2] National Institute for Nuclear Physics (INFN) – Padua Division
Via Marzolo 8, 35131 – Padova, Italy
E-mail: marco.azzolin@unipd.it

Abstract. Recent advancements in the field of additive manufacturing have enabled the realization of products that were previously almost unattainable. In the field of heat transfer, the production of heat exchangers through additive manufacturing is promising because it allows for the creation of more compact heat exchangers that can be tailored to specific requirements with optimized and complex geometries. However, also heat transfer devices that must be specifically realized for heat transfer research purposes can benefit from the characteristics of the additive manufacturing technology. This paper presents an innovative test section created through additive manufacturing technology with the aim to investigate two-phase heat transfer of refrigerants inside a 2.9 mm internal diameter channel. Water is used as a secondary fluid to reject/extract the heat. As a first step, a CFD analysis was performed to design a special geometry for the test section allowing a local measurement of the heat transfer coefficient along the channel. The test section was realized with the DMLS (Direct Metal Laser Sintering) technology using the AlSi10Mg alloy. Despite the benefits introduced by this manufacturing process, DMLS technology can lead to anisotropy in the thermal conductivity of the test section material. Thus, cylindrical samples were produced by DMLS with different building orientations to perform specific measurements of the thermal conductivity by using the Hot Disk technique. Preliminary local heat transfer coefficients were measured with refrigerant R1234ze(E) during condensation at 40 °C saturation temperature and mass flux 150 - 200 kg m^{-2} s^{-1}. Experimental heat transfer results are compared against predictions obtained from a correlation available in the literature.

1. Introduction

A complete understanding of two-phase heat transfer in small diameter channels is still far from being achieved and represents a contemporary research topic. Small diameter channels have increasing application possibilities in compact heat exchangers for electronic cooling systems, thermal control of satellites, automotive batteries thermal control, refrigeration and heat pump systems. Beyond their advantages related to the compactness of the device, minichannels offer additional environmental and operational benefits. Notably, these systems allow a reduction of the refrigerant charge, a sought after feature when using natural fluids that are flammable (e.g hydrocarbons) or toxic (e.g. ammonia). Furthermore, compact heat transfer devices are usually capable of working with high-pressure fluids (es. carbon dioxide), as their reduced size makes them suitable for withstanding elevated pressures. The design of two-phase heat exchangers with reduced internal diameters requires the availability of correlations validated against wide experimental database. Measuring two-phase heat transfer coefficients inside small diameter channels is challenging due to the small heat flow rates to be measured and to the high expected values of the two-phase heat transfer coefficients which require a direct measurement of the internal wall temperature.

Del Col *et al*. [1] investigated local heat transfer coefficients during condensation of R1234ze(E) in a single circular minichannel with a diameter equal to 0.96 mm. Thermocouples were installed in holes drilled near the wall of the internal channel and also inserted in the external water channel to get the water temperature profile and the local heat flux. Condensation heat transfer experiments were conducted over a range of mass velocities from 100 kg m^{-2} s^{-1} to 800 kg m^{-2} s^{-1}, at a saturation temperature equal to 40 °C. Quasi-local heat transfer coefficient were measured by Azzolin *et al*. [2] during R1234ze(E) condensation inside a circular microchannel with a 3.38 mm diameter. Del Col *et al*. [3] investigated local heat transfer coefficients at different inclinations with R32 and R134a flowing inside a square channel having hydraulic diameter equal to 1.23 mm.

The recent progresses in additive manufacturing techniques pave the way for the realization of more complex test sections for the study of condensation and flow boiling heat transfer inside small size channels. In this study, a new test section was designed, fabricated and instrumented to measure local heat transfer coefficients during two-phase heat transfer inside a horizontal channel having an internal diameter equal to 2.91 mm. The test-section was built via additive manufacturing technique with the aluminium alloy AlSi10Mg. The structure of the test section can be considered as the one of a tube-in-tube heat exchanger: the refrigerant flows inside the 2.91 mm diameter tube whereas the water flows in counter-current through a complex passage realized on the external side. A preliminary CFD analysis was performed to find the optimal geometry of the water path with the aim to improve the accuracy in the measurement of the heat transfer coefficients along the tube.

2. Test section design and construction

The objective of this study was the design and the realization of a test section for local two-phase heat transfer measurements of refrigerants and using water as secondary fluid. The test section is made of two sectors in which the water and the refrigerant flow in counter-current (Figure 1a). In each sector, the mass flow rate and the inlet temperature of the water can be independently controlled. To obtain the local heat transfer coefficient the following three quantities must be measured: the local heat flux, the wall temperature of the surface in contact with the refrigerant, and the saturation temperature. By measuring the water temperatures along the tube it is possible to get the local heat flux. It is therefore crucial to find a finned geometry for the cooling water circuit that is able to guarantee a high measurement accuracy of the local heat flux.

A CFD analysis was performed to find the geometry for the fins, their number and spacing along the pipe axis. Simulations were run imposing the following boundary conditions: water mass flow rate, inlet water temperature, refrigerant heat transfer coefficient and saturation temperature. The simulation outcomes were employed to analyse the temperature distribution in both the aluminium alloy structure and in the water. The primary objective is to identify the proper locations for thermocouples placing. In terms of wall temperature measurements, the results indicate that the most favourable location for sensor installation is at the midpoint of a fin. Figure 1b illustrates the temperature field in the middle section of a fin located at the centre of the sector considering a water mass flow rate equal to 15 kg/h and a refrigerant side heat transfer coefficient equal to 5000 W m^{-2} K^{-1}. Figure 1b shows the capability of the geometry under consideration to produce a uniform temperature distribution along the fin. The discrepancy between the highest and lowest temperatures on the aluminium body is around 0.5 K: a thermocouple installed in a hole 1 mm far from the internal wall will measure a temperature that is only 0.2 K lower compared to the internal wall surface. A similar analysis was performed for the temperature in the water flow. Figure 1c shows the temperature distribution of the water flowing through a fin cut halfway along the length of the sector. The finned geometry on the water side has been designed with the objective that a thermocouple installed in correspondence of a fin cut can get the measurement of the adiabatic mixing temperature. From the simulations, the discrepancy between the measured water temperature at the centre of the fin cut and the adiabatic mixing temperature is around 0.1 K.

a)

b)

c)

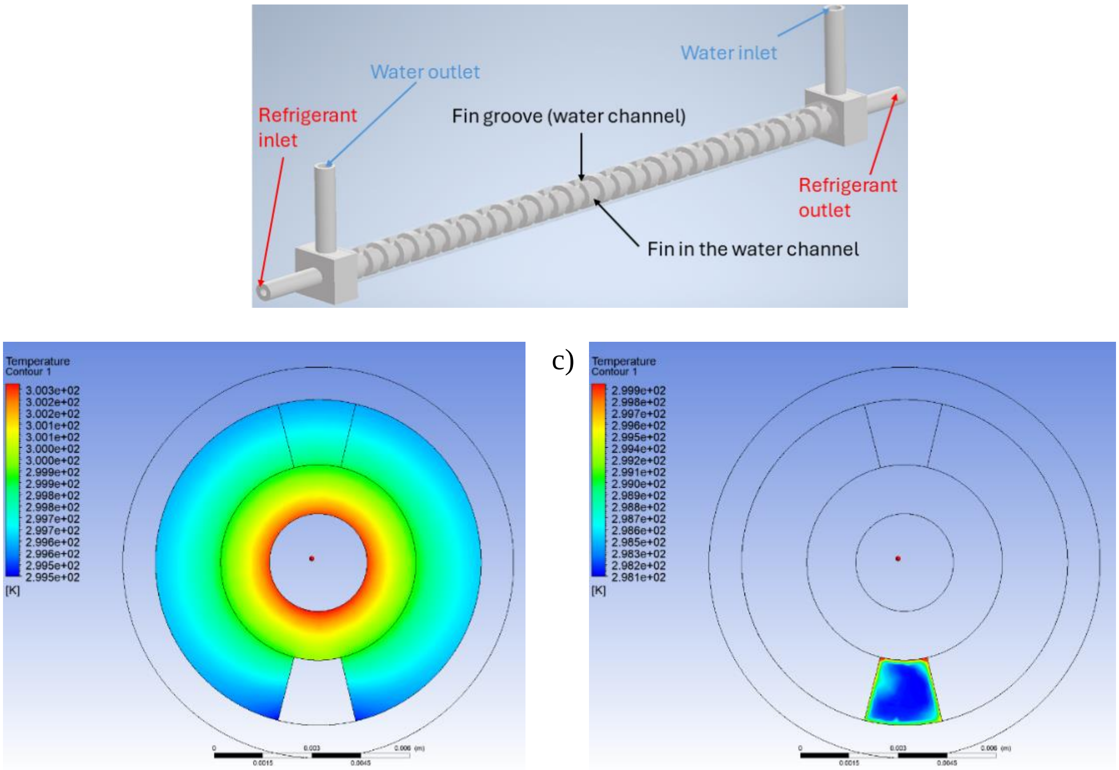

Figure 1. a) Sketch of the test section showing the finned water path. b) Computed temperature field in the middle section of the fin indicated in a) with the black arrow. (c) Water temperature distribution calculated in the cross section of the groove (indicated with a black arrow) inside which a water thermocouple is placed.

The test section was manufactured using EOSINT M280 powder bed machine equipped with a 400 W ytterbium fibre laser. With the aim to reduce possible variations of the internal dimensions of the channel and to control its surface roughness, electrical discharging machine has been used for the surface finish of the 2.91 mm diameter channel. To assemble the whole test-section, two tube-in-tube heat exchangers (sectors) were instrumented and connected in series. Each of the two sectors was equipped with 8 thermocouples for the water temperature and 8 thermocouples for the wall temperature measurement. In addition, a thermopile and two thermocouples were inserted in the inlet and outlet water ports of each sector to double-check the water temperature difference. Figure 2 shows the test-section after the installation of the temperature sensors.

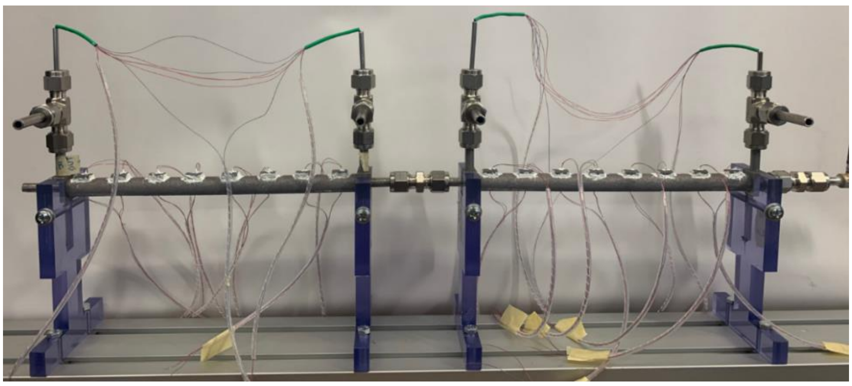

Figure 2. Image of the test-section realized by additive manufacturing after the installation of the water and wall thermocouples. The two sectors are visible with the inlet and outlet ports for the water.

3. Measurements of the thermal conductivity for the AlSi10Mg aluminium alloy

Despite the benefits introduced by the additive manufacturing (AM) process, AM-produced parts can display some thermal conductivity anisotropy. The knowledge of the thermal conductivity of the test section material, and its possible variation with the direction, is very important for the design of the heat transfer section. In fact, as reported in Sec. 4., for the measurement of the local heat transfer coefficient, the temperature at the inner wall of the channel (T_{wall}) must be determined. The inner wall temperature is obtained from the readings of thermocouples installed inside holes drilled 1 mm away from the internal surface of the channel. The measured temperature must be corrected to account for the thermal conduction inside the AlSi10Mg channel wall.

A study was conducted to measure the thermal conductivity of the AlSi10Mg aluminium alloy produced via the same additive manufacturing process adopted to build the test-section. For this purpose, three sets of cylindrical samples were printed with different building orientations with respect to the horizontal plane: 0°, 45° and 90°. The equipment used for the measurements is a Hot Disk TPS 3500 thermal constant analyser (Figure 3a). The measurement process of the samples' thermal conductivity is based on the transient plane source method (TPS). A flat sensor is located between two specimen halves and it acts both as a temperature sensor and as a heat source. During the tests, the hot disk sensor supplies a constant electrical power and at the same time it measures the temperature rise caused on the specimen's active surface, by monitoring the sensor's electrical resistance variation. The ideal model of the measurement process is based on the assumption of a semi-infinite material. This can be obtained using samples with dimensions sensibly larger than the sensor radius. For this purpose, the samples were built with a diameter of 50 mm and a height of 16 mm, which were considerably larger than the diameter of the sensor. Furthermore, the measurement time is chosen in such a way that the heat propagating through the material does not reach the boundary material during the test.

a) b)

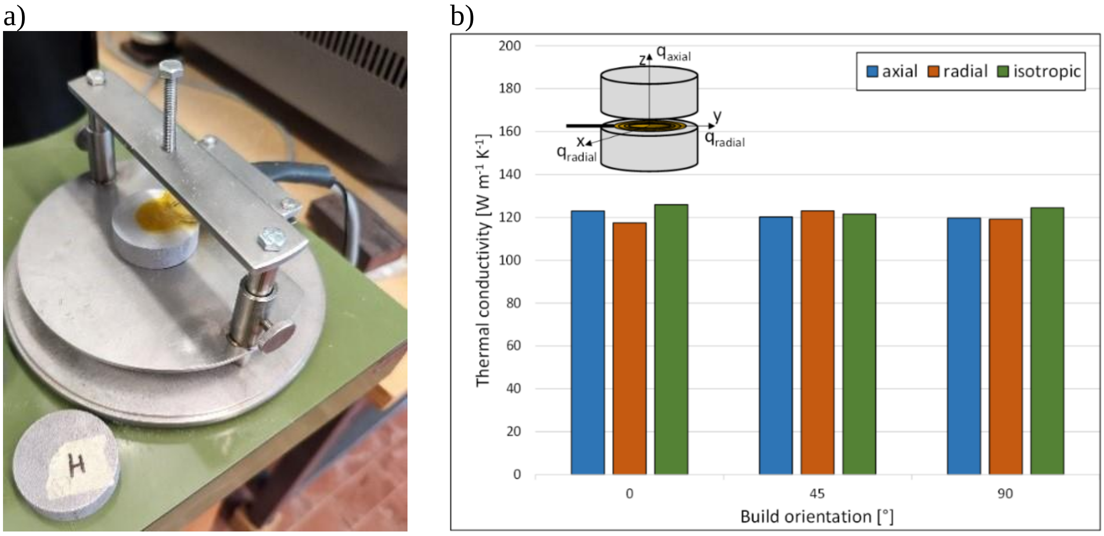

Figure 3. a) Image of the Hot Disk TPS 3500 measurement system used during the test. b) Measured values of thermal conductivity performed with the Hot Disk isotropic and anisotropic models (axial and radial directions). Measurements refer to three construction orientations with respect to the horizontal plane (0°, 45° and 90°).

Experimental measurements were carried out at room temperature using the anisotropic module of the Hot Disk TPS 3500 instrument on each of the AM samples, setting a supplied electrical power and measurement time equal to 2 W and 2 s respectively. These parameters have been optimized in order to avoid that the propagating heat flux reached the outer boundaries of the material during the tests. Selected points of calculation (20-150) were chosen, neglecting the firsts and lasts measured data because they can be affected by the boundary conditions. A volumetric specific heat of 2.4 MJ m^{-3} K^{-1} was used as input. Experimental measurements performed with both the anisotropic and isotropic models showed a negligible difference between the thermal conductivity measured with samples having different building orientations with respect to the horizontal plane (0°, 45° and 90°). Figure 3b summarizes the obtained results. The presented values are the mean of at least five repeated measurements. The measured differences between thermal conductivities are equal to 3.6% using the isotropic model, and 4.8% with the anisotropic one. These values are lower than the experimental uncertainty. Therefore, no anisotropic behaviour was observed for the tested samples. The average value of thermal conductivity, which was adopted during the data reduction process described in the next sections is equal to 121.5 W m^{-1} K^{-1}.

4. Condensation tests: data reduction and experimental results

4.1. Data reduction

The condensation heat transfer coefficient (HTC) at a given position z along the 2.91 mm internal diameter channel can be obtained from the measurements of three quantities: the heat flux $q(z)$, the saturation temperature (T_{sat}) and the wall temperature T_{wall}, as reported in equation 1. The saturation temperature changes along the tube as the saturation pressure decreases due to pressure drop. Pressure ports are installed at the inlet and outlet of the test section and a linear variation of the saturation pressure along the channel is assumed.

$$\mathrm{HTC}(z) = \frac{q(z)}{T_{sat}(z) - T_{wall}(z)} \tag{1}$$

The local heat flux $q(z)$ is determined from the derivative of the water temperature profile measured along each of the two sectors of the test section (equation 2). To achieve this, the data from the eight water temperature measurements obtained in each sector are fitted by a function whose coefficients are obtained from the method of least squares. In equation 2, c_w is the water (secondary fluid) specific heat, D is the internal diameter of the channel, and $\dot{m}_w$ is the water mass flow rate.

$$q(z) = \frac{\dot{m}_w\, c_w}{\pi\, D} \frac{\mathrm{d}T_w(z)}{\mathrm{d}z} \tag{2}$$

4.2. Experimental results

Figure 4a shows the local heat transfer coefficients measured during condensation of R1234ze(E) inside the 2.91 mm diameter channel.

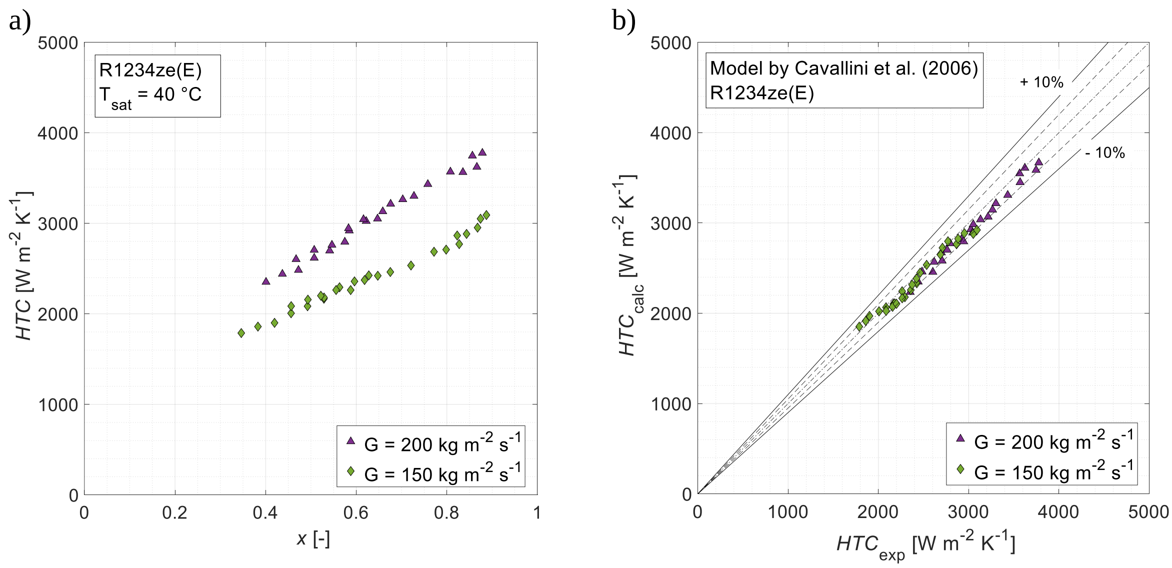

Figure 4. a) Local heat transfer coefficients measured during condensation of R1234ze(E). b) Experimental heat transfer coefficients compared against the correlation by Cavallini *et al.* [4].

Each data series refers to a fixed value of mass flux (G = 150 kg m^{-2} s^{-1} and G = 200 kg m^{-2} s^{-1}) and heat transfer coefficients are measured at different values of vapour quality and thus at different axial location z along the two sectors of the test section. It can be observed that moving from the lowest to the highest tested mass flux, the heat transfer coefficient is increased on average by 24%. Figure 4b shows the comparison between the experimental heat transfer coefficients and the predictions obtained applying the correlation developed by Cavallini *et al*. [4]. All the present data are accurately predicted by the selected correlation (88% of the experimental data fall within a ± 5% deviation range).

Conclusions

In this work, a new aluminium alloy test-section was fabricated with additive manufacturing to perform local measurements of two-phase heat transfer coefficients inside a circular channel with an internal diameter equal to 2.91 mm. A preliminary CFD analysis was performed to design the test section and to determine the position for the thermocouples in the channel wall and inside the water (secondary fluid) path. The thermal conductivity of the aluminium alloy was measured along different directions using the Hot Disk TPS technique. The experimental tests showed that the material is not characterized by anisotropic behaviour regarding the thermal conductivity, and allowed a precise determination of the thermal conductivity, which is a key parameter for the calculation of the refrigerant side heat transfer coefficient.

The new test-section was used to investigate local heat transfer coefficients during R1234ze(E) convective condensation inside a 2.91 mm diameter channel. Tests were performed at a saturation temperature equal to 40 °C and varying the refrigerant mass flux from 150 kg m^{-2} s^{-1} to 200 kg m^{-2} s^{-1}. It was found that the heat transfer coefficient increases as the mass flux and vapour quality increase. The experimental data were compared with the correlation developed by Cavallini *et al*. [3] which was found to provide an accurate prediction of the measured heat transfer coefficients, with 88% of the experimental data predicted within the ±5% deviation band. The new test section will allow the installation of a glass window for flow visualization and the possibility to study two-phase heat transfer with natural fluids like ammonia. The outcomes will provide essential information to achieve a better understanding of the physical phenomena involved in the condensation process.

Acknowledgments

Financial support by MUR (Research Project of National Interest PRIN 2022 MOOD4HEX - MOrphology Optimized Design for Heat EXchangers) is acknowledged. This work has been also supported by MASE – ENEA program “Ricerca di Sistema Elettrico – Piano Triennale di Realizzazione PTR 2022–2024 – Tecnologie per la penetrazione efficiente del vettore elettrico negli usi finali”. The authors would like to thank DIAM (Development and Innovation on Additive Manufacturing, https://www.pd.infn.it/eng/diam/) Laboratory for the work done during the realization of the heat transfer test section.

References

[1] Del Col D, Bortolato M, Azzolin M and Bortolin S 2015 Condensation heat transfer and two-phase frictional pressure drop in a single minichannel with R1234ze(E) and other refrigerants *Int. J. Refrig.* **50** 87–103

[2] Azzolin M, Berto A and Bortolin S 2022 Condensation heat transfer of R1234ze(E) and its A1 mixtures in small diameter channels *Int. J. Refrig.* **137** 153–165

[3] Del Col D, Bortolato M, Azzolin M and Bortolin S 2014 Effect of inclination during condensation inside a square cross section minichannel *Int. J. Heat Mass Transf.* **78** 760–77

[4] Cavallini A, Del Col D, Doretti L, Matkovic M, Rossetto L, Zilio C and Censi G 2006 Condensation in horizontal smooth tubes: A new heat transfer model for heat exchanger design *Heat Transf. Eng.* **27** 31–8