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Spray cooling of electronic devices with R410A refrigerant

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Abstract – The development of smaller and more powerful electronic devices is limited by the challenge of effective cooling. In many cases, active thermal management techniques have become necessary, and spray-cooling with refrigerants has emerged as a promising solution. This study aims to investigate the effects of the distance between the nozzle and the surface, as well as the mass flow rate of the refrigerant, in a spray cooling configuration using R410A refrigerant. The results indicate that as the imposed heat flux increases, there is an increase in surface superheat. Higher nozzle flow rates cause a shift of the corresponding curves to lower superheat values. The heat transfer coefficient gradually increases with the heat flux until it reaches a peak value, and then decreases for higher heat fluxes. Increasing the distance between the nozzle and the surface appears to delay the decline of the heat transfer coefficient at higher heat fluxes.

1. Introduction

Power electronic devices and systems are used in a continuously increasing field of consumer and industrial applications. Following the trend to develop smaller and more powerful electronic devices, effective cooling has become a limiting factor. Therefore, active thermal management techniques are necessary in order to enable higher power densities, optimal control, and reduction of temperature peaks and swing amplitudes, leading to an increase of performance efficiency and life expectancy. To this end, spray-cooling with the use of refrigerants has emerged as a promising option, having the ability to dissipate large amounts of heat, while the surfaces of the electronic components can be maintained at a low and uniform operating temperature range, by suitable selection of refrigerant. Spray-cooling heat transfer is characterized by the combined effect of liquid film evaporation over the sprayed surface, turbulent forced convection heat transfer due to the impact of the sprayed droplets, formation of active nucleation sites and the creation of secondary nucleation points on the surface of the impinging droplets [1]. In this work a spray cooling configuration utilizing R410A is investigated experimentally, with respect to the nozzle to surface distance and refrigerant mass flow rate.

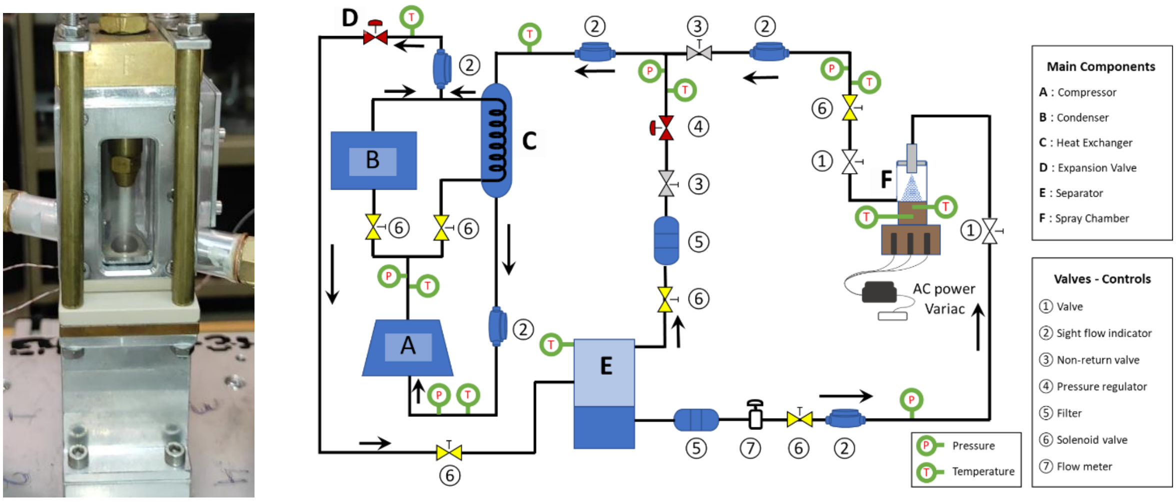
2. Experimental Setup and Procedure

2.1 Spray chamber configuration

The spray cooling assembly, shown in Figure 1.a, comprises an aluminum block base, incorporating four heating resistors (4 x 400 W). Heat is transmitted through a block of pure copper (k=385 W/m K), with a cylindrical neck machined at its upper part. The cylindrical surface of the neck is insulated by Peek material to achieve one dimensional heat transfer along its axis. Heat flux is measured by two K thermocouples, placed at a distance of 7 mm along the axis. The upper surface of the neck simulates the surface of the electronic device and is cooled by the impinging refrigerant jet. The spray chamber is cylindrical with diameter 30 mm, machined from an aluminum block. Two Perspex windows, with internal surface following the cylindrical form of the chamber, provide optical path to the chamber interior and the cooling surface. The refrigerant jet issues from a solid cone pressure swirl spray nozzle (Danfoss OD 5 USgal/hr, 60° spray angle), attached to the brass upper casing of the spray chamber, with interchangeable nozzle tubes, which determine the nozzle to surface distance. The refrigerant is suctioned out of the chamber via two 8 mm diameter run-off holes. The assembly is stressed by four rods, pressurizing suitable O rings between the components to ensure gas tightness of the chamber, whereas Kryonaut thermal conductive grease is applied between the copper block and the resistors aluminum casing to reduce contact thermal resistance. The whole assembly is covered with thick layers of insulating material (not shown for presentation purposes).

2.2 Closed refrigeration loop

The closed refrigeration loop is based on a modified refrigeration cycle, using several components of a residential inverter HVAC unit, of 3.5 kW (12000 Btu/hr) thermal capacity. The eco-friendly (zero ODP) near-azeotropic coolant R410A is used as working fluid, having a suitable saturation temperature range [2-3]. As shown in the diagram of Figure 1.b, the main components include a compressor (A), a condenser (B), a heat exchanger (C), an expansion valve (D), a liquid-vapor separator (E) and the spray chamber (F). The loop is also equipped with valves and regulators to control system operation, and measuring devices to monitor pressure, temperature and flow rate at several locations, as shown in Figure 1.b. Measurements are recorded and stored in computer memory for further processing, via suitable data acquisition hardware and software.



(a) (b)

Figure 1: (a) The spray chamber assembly, (b) Diagram of the closed refrigeration loop

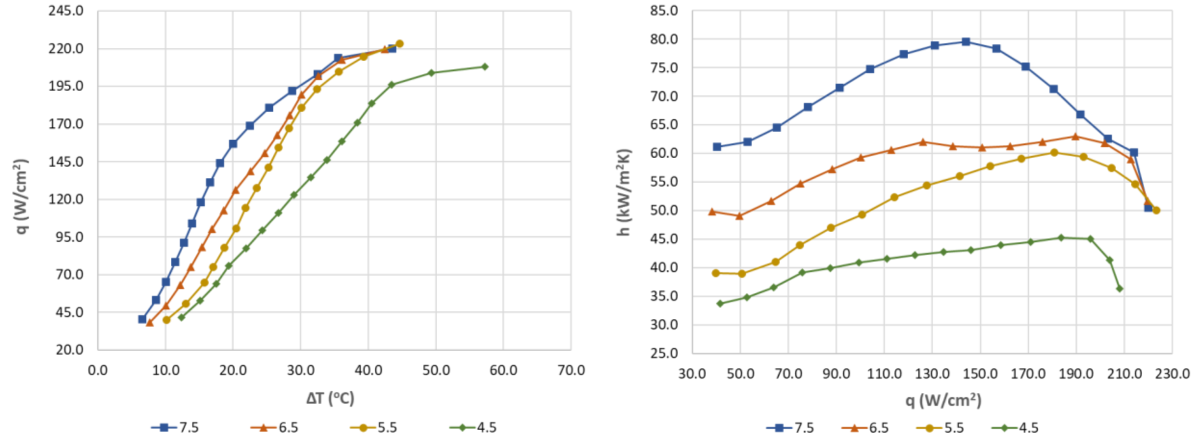
2.3 Experimental procedure

The electric power consumed by the heating resistors is regulated by a PID controller. The measurement of the heat flux along the copper neck shows that a large percentage of the released heat is passing through the neck, indicating an efficient insulation of the spray chamber assembly. Experiments comprise measurements of the heat flux and heat transfer coefficient in relation to surface superheat, for four spray heights (15, 20, 25 and 30 mm), and four mass flow rates through the nozzle (4.5, 5.5, 6.5 and 7.5 g/s), for several settings of the electric power consumption and thus heat fluxes at the spraying surface. Measurements were obtained with careful control of the regulation valves, to obtain the required mass flow rate and ensure that the fluid was superheated vapor at compressor inlet and subcooled liquid at the nozzle inlet. The high pressure of the compressor was close to 30 bar, whereas the spray chamber had a pressure close to 5.3 bar, corresponding to a saturation temperature of -12 °C. At each setting, measurements were obtained after a 30 min settling period, for the system to reach steady state conditions.

3. Experimental Results

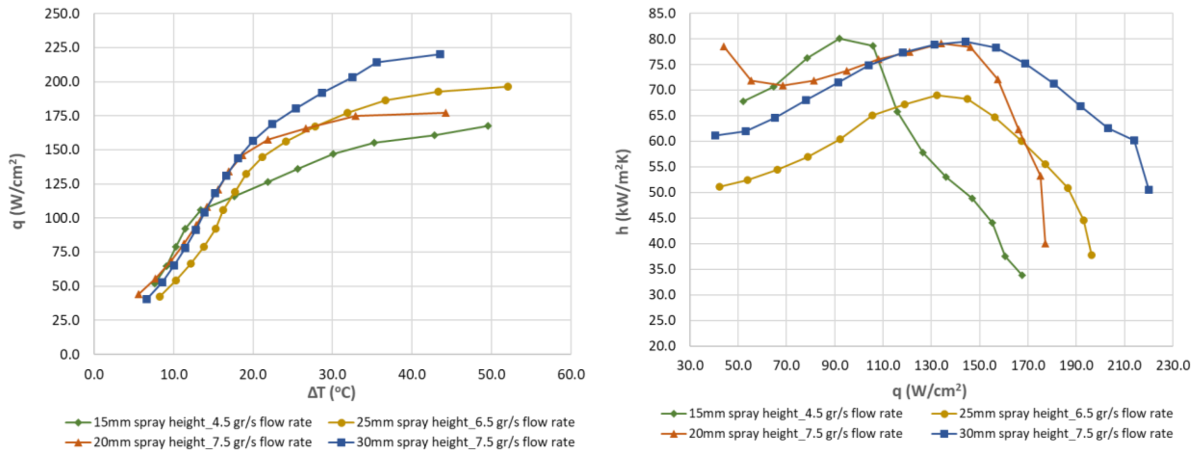
Typical results of this investigation are presented and discussed in the following. The effect of the mass flow rate, for a nozzle distance of 30 mm, is presented in Figure 2. Figure 2.a indicates that the superheat of the surface in comparison to the saturation temperature is in general decreased, as the flow rate of the refrigerant through the nozzle is increased, probably due to the intensification of the turbulence by the more vigorous impingement of the spray droplets on the surface. At low heat fluxes the required superheat is increasing in an almost linear trend with the applied heat flux. The corresponding diagrams of the heat transfer coefficient (Figure 2.b) indicate that, at low heat fluxes, the heat transfer process is gradually improved, through the interplay of the mechanisms mentioned in the introduction, for all flow rates. The highest value close to h=80 kW/m^{2}K, is reached at imposed heat flux q=140 W/cm^2, for flow rate 7.5 g/s. For all flow rates, the heat transfer coefficient is decreasing quite rapidly after the peak. This trend is related to the transition to film boiling in pool boiling experiments, when the vigorous production of vapor close to the surface impedes the liquid to reach the surface, and the heating surface is abruptly fully covered by vapor, resulting in a tremendous increase of superheat. In the case of spray cooling, this sudden change seems to be prevented, probably because the impact of the droplets on the surface undermines the stability of the continuous vapor film, leading to the formation of film boiling spots on the surface. At these conditions small increases of the heat flux result in large increases of the superheat (Figure 2.a). The experiment has to be stopped, before the stability of a fully covering vapor film is established at a critical heat flux, which would result in an enormous surge in superheat.

The effect of the interplay between mass flow rate and nozzle to surface distance is further illustrated in Figure 3, where the optimal flow rate results for each distance are presented. It is interesting to observe that the highest flow rate in not always the optimal for each distance, a fact related also to the actual spray pattern of the nozzle. For the smallest nozzle distance, the optimal heat transfer coefficient, close to h=80 kW/m^{2}K, is obtained at q=90 W/cm^2, for flow rate 4.5 g/s. The decline of the heat transfer coefficient is thereafter quite steep. For the nozzle to surface distance 20 mm, a heat transfer coefficient peak close to the same value is obtained at higher heat flux, q=130 W/cm^2, for the highest flow rate of 7.5 g/s. At higher heat fluxes the heat transfer coefficient decline is even steeper. The best overall performance in a wide range of heat fluxes, seems to be obtained at nozzle distance 30 mm, for the highest flow rate of 7.5 g/s.



(a) (b)

Figure 2: Mass flow rate effect for 30 mm nozzle distance (a) Surface superheat vs heat flux, (b) Heat flux vs heat transfer coefficient



(a) (b)

Figure 3: Optimal mass flow rate performance per nozzle distance (a) Surface superheat vs heat flux, (b) Heat flux vs heat transfer coefficient

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