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Characterization of spray atomization and heat transfer for a swirl nozzle

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Abstract.

Spray cooling, a high heat flux thermal management, has received great attention from modern industrial and technological applications, such as power electronics, high-power lasers, and conversion systems etc. The focus of the present work is to investigate the spray characteristics and heat transfer of a swirl nozzle under a low pressure drop range. An open loop spray cooling system is developed to examine the heat transfer performance of the swirl nozzle by considering the effects of nozzle pressure drop, impinged spray height. A Phase Doppler Anemometry (PDA) system is applied to characterize the droplet Sauter Mean diameter, droplet velocity, spray angle, and spray pattern. It is found that the swirl nozzle under lower pressure drop helps to generate a full cone spray with a smaller spray angle, while the higher pressure drop produces better atomization quality. The heat transfer experimental results indicate that the droplet impingement is the primary cooling mechanism in the non-boiling regime of spray cooling, and increasing the pressure drop generally improves the heat transfer performance.

Key words

Swirl nozzle, Sauter Mean diameter, spatial distribution, spray cooling

1. Introduction

Recently high heat flux thermal managements have received great attention from the modern industrial and technological applications, such as power electronics, high-power lasers, and conversion systems etc. Spray cooling is considered as a promising candidate to fulfil this cooling requirement due to its best balance on high heat flux removal capability, isothermality, low superheat, and small fluid inventory [1].

Spray cooling occurs when liquid forced through a small orifice shatters into a dispersion of fine droplets which then impact onto the surface being cooled. The spray characteristics, such as droplets diameter, velocity, number flux and spray pattern affect the heat transfer of spray cooling in nature. Chen et al. [2] reported that the droplets velocity and droplets flux have prominent effect on heat transfer performance in spray cooling. However, the droplets diameter has negligible effect. They further concluded that the dilute spray with high droplet velocity would be more effective than the dense spray with low droplet velocity in achieving high heat flux at a given flow rate. Estes and Mudawar [3, 4] indicated that the spray with higher Weber number resulted in a suppression of nucleation and liquid evaporation, while the liquid with low Weber number displayed a more pronounced increase of liquid evaporation efficiency. However, Chen et al. [5] believed that the droplets flux is most important in spray cooling due to the mechanism of 'secondary nuclei'.

It is easy to argue that a suitable spray nozzle will give an advantage to the heat transfer performance in spray cooling by its favourable spray characteristics. In general, a higher pressure drop produces better atomization quality by generating finer droplets, larger spray angle, and higher droplet velocity [6]. However, in spray cooling the higher pressure drop may cause a major issue on the system reliability [7]. For this reason, swirl nozzle could be a better choice in spray cooling applications as it is able to produce a good atomization quality when the applied pressure energy is in a low range [6]. Nevertheless, in literature, few of the studies on swirl nozzles were conducted under low pressure drop.

A survey of literature shows that most of the studies on spray cooling are concentrating on small surface area (1-2 cm^2) by using a single spray nozzle. However, there are limited research reports on using a swirl nozzle to cool a large surface area. Thereby, in the present study, a swirl nozzle was carefully sourced and investigated at different distances downstream from the nozzle tip under a low pressure range (3 bar and 4 bar). The effects of pressure drop and spray height on spray angle, droplets size, and droplet flux distributions were investigated using an optical diagnostic technique, in particular, a Dantec Phase Doppler Anemometry (PDA) system. In addition, an open loop spray cooling system was set up to study the heat transfer performance on a relatively large heated surface area in the non-boiling regime.

2. Experiment apparatus

The experimental setup in the present study mainly consists of three systems: the liquid delivery system, the spray characterizing system, and the heat transfer system. The schematic of the entire experimental setup is demonstrated in Fig. 1.

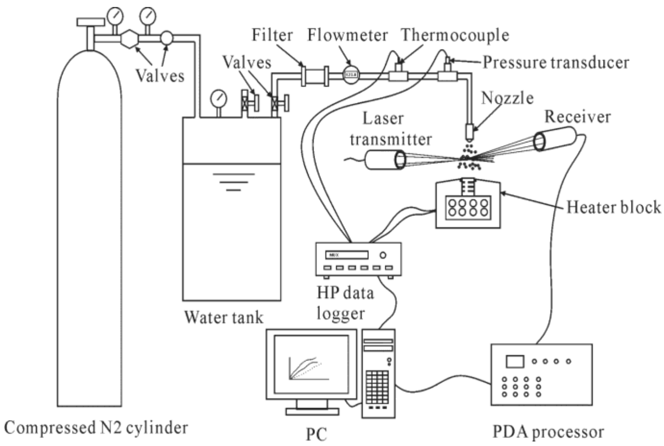
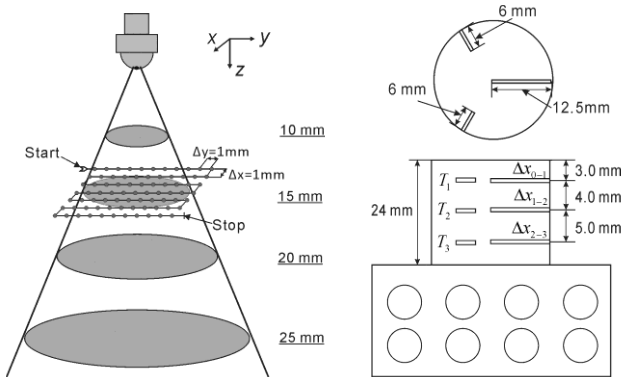


Fig. 1 Schematic of the experimental setup

Several equipment are used in the setup of the liquid delivery system. A compressed N2 tank and a stainless-steel water tank supply the pressurized water. A shut-off valve is used to switch on/off the main line flow, and an in-line filter to filtrate the impurities in water. Also, a digital turbine flow meter measures the flow rate, a housing thermocouple measures the inlet water temperature, and a pressure transducer measures the pressure drop across the spray nozzle. In this system, a full cone swirl nozzle (Steinen) was employed for the liquid atomization.

The Dantec PDA system with Ar-ion laser as light source was employed to measure the droplet size, droplet velocity, droplet number flux and spray angle. During the PDA measurement, the spray nozzle was fixed on a vertical test stand and the measuring volume of the PDA system was allowed to translate in *x*, *y* and *z* directions to characterize the spray at different planes downstream of the nozzle tip (10 mm, 15 mm, 20 mm and 25 mm), as shown in Fig. 2(a). The PDA measurements have been conducted by following a measuring grid trajectory to cover the whole spray cone at the respective plane.



(a) (b)

Fig. 2 Schematic of experimental measurement: (a)PDA measurement, (b) thermocouple locations

In the PDA measurement, Sauter Mean Diameter (D_{32}) was chosen to characterize the statistic droplets size at each plane,

$$D_{32} = \frac{\sum_{i=1}^{n} D_i^3}{\sum_{i=1}^{n} D_i^2} \qquad (1)$$

where D_i is the diameter of the *i*th droplet, *n* is the total number of droplet samples captured by the PDA system. The droplet flux fraction η is defined as the ratio of local droplet number flux (N_i) at a measurement point to the total number of droplets (N_{total}) of all the measurement points along a diameter of the spray cone,

$$\eta = \frac{N_i}{N_{Total}} \times 100\% \qquad (2)$$

and it is used to represent the spatial droplet density distribution of the spray cone at the respective plane.

In the heat transfer system, the heater was made of a pure copper block and was heated by eight 150 W cartridge heaters which were placed as shown in Fig. 2(b). Before fabricating the heater, the height of the neck cylinder was carefully designed by using the Steady-State Thermal model of ANSYS to achieve a one-dimensional heat transfer characteristics below the test surface. Nine K-type thermocouples with 0.3 mm in bead diameter were embedded into the copper block in three layers where the one-dimensional heat transfer characteristics are still satisfied. At each thermocouple layer, the three thermocouples were separated by 120°. One of thermocouples was installed to measure the temperature at the centre of the test surface, and the other two thermocouples were installed to measure the temperatures at the radial distance of 6.5 mm off the surface centre. Knowing the temperature gradient between the neighbouring thermocouple layers, the applied heat flux and the corresponding surface temperature could be calculated by the one-dimensional Fourier law of heat conduction.

In the experiment, the digital turbine flow meter, pressure transducer, and thermocouples were all calibrated before being installed in the experimental setup. A HP

BenchLink Data acquisition system was employed to record and process the signal from the thermocouples as well as the pressure sensor throughout the experiments.

3. Results and discussion

3.1 Spray characteristics

In the PDA experiments, the spray parameters, mainly the droplet Sauter mean diameter, droplet velocity and spray pattern were investigated, and the general parameters of the spray nozzles are shown in Table I.

Table I. Spray characteristics of swirl nozzle

Spray height (mm)	Δp = 3 bar		Δp = 4 bar	
	Spray angle(°)	D_{32} (μm)	Spray angle(°)	D_{32} (μm)
10	70	196	74	174
15	64	189	67	158
20	61	173	63	145
25	56	159	57	137

During the liquid atomization process in Fig. 3, it is observed that the liquid spreads as a conical film sheet as soon as it leaves the nozzle's orifice. Thereafter, the conical film sheet with high velocity finally disintegrates into several ligaments and then fine droplets due to the instability caused by the velocity slip between the liquid film and ambient air. As the liquid film is dispersed, a curved boundary is observed between the spray cone and ambient air. Therefore, the measured spray angle decreases as the spray height increases as tabulated in Table I. It is also observed that the droplets size D_{32} decreases with the increasing of spray height. This is mostly due to the short range of spray height, from which the droplets breakup is the dominant behaviour of the droplets, while the droplets coalescence effect is insignificant. As the pressure drop increases, the finer droplets is generated, which could be attributed to the increased kinetic energy of the atomizing liquid which improves the atomization quality [6].

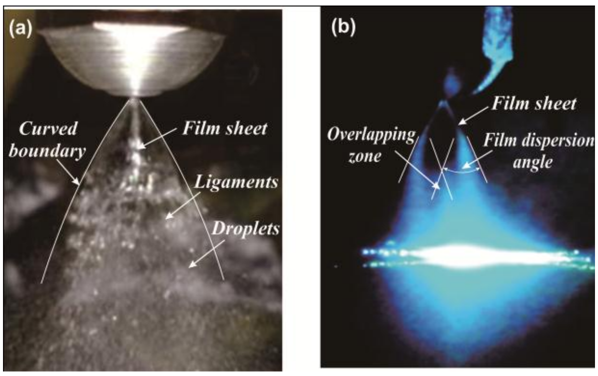


Fig. 3 Liquid atomizing behaviour of FN3 nozzle: (a) in free spray; (b) in PDA measurement

Fig. 4 illustrates the axisymmetric spatial distributions of droplets flux fraction and mean axial velocity at the measurement planes of z = 10, 15, 20, and 25 mm, and two pressure drops (3 bar and 4 bar) were investigated. It is observed that the investigated swirl nozzle produces a full cone spray when a certain spray height is ensured, and the droplet velocity distribution has the similar trend as the droplet flux distribution.

At the pressure drop of 3 bar, the swirl nozzle results in two local droplet flux peaks and one local droplet flux valley along the diameter of the spray cone at the short spray height in Fig. 4(a). As the spray height increases, the difference between the peak and valley values decreases causing a more uniform distribution. When the spray height reaches 25 mm, a single droplet flux peak is finally attained at the spray cone centre. This phenomenon could be explained by the droplets overlapping in the spray cone after they are dispersed from the liquid film, as depicted in Fig. 3(b). It can be seen that, the liquid film is dispersed into fine droplets with a certain dispersion angle in the liquid atomization process, from which the droplets overlap at the spray cone centre when the required spray height is ensured. As spray height increases further, the droplets overlapping is accumulated to enhance the droplet flux at the spray cone centre so that a peak value is finally obtained at the spray height of 25 mm.

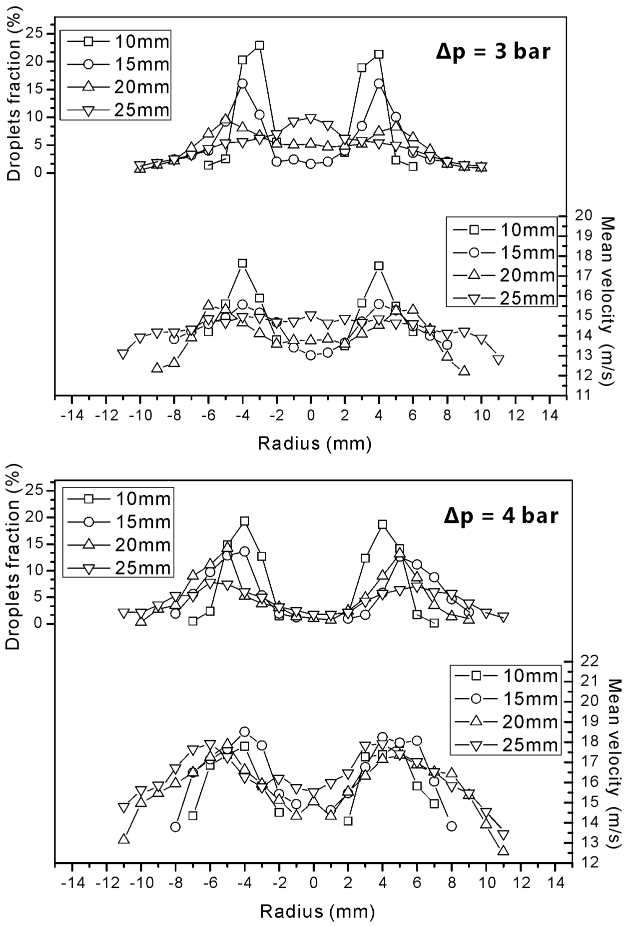


Fig. 4 Spray pattern of the swirl nozzle

At the pressure drop of 4 bar, it is observed that this swirl nozzle is not able to generate a peak droplet flux at the centre even the spray height is 25 mm, and the occurrence spray height for a full cone spray is also delayed from 15 mm at the pressure drop of 3 bar to 20 mm. This could be due to the larger spray angle resulted at the higher pressure drop which requires a larger spray height for droplets overlapping.

The comparison between the spatial distributions of droplet flux fraction and mean axial velocity shows that the higher mean velocity is obtained at the locations where the denser droplet flux occurs. It is reasonable that the droplets at the locations with dense droplet flux usually have larger velocity momentum thereby they are less affected by the drag effect of the steady ambient air. As the spray height increases, the droplet velocity decreases correspondingly due to the longer travel path in the steady ambient air.

3.2 Surface temperature distribution

As shown in Figs. 5 and 6, the surface temperature distributions under different impinged spray heights and applied heat flux are presented. It is observed that the distribution of surface temperature behaves in an axisymmetric manner as similar to the droplet flux distribution.

In Fig.5, with the low applied heat flux of 28.92W/cm^2, a lower surface temperature ($T_{r=0}$ at r = 0 mm) is obtained at the centre of the heater cylinder when the impinged spray height is 5 mm, and a higher $T_{r=0}$ at the impinged spray height ranging from 10 to 20 mm. As the impinged spray height reaches 25 mm, a lower surface temperature is observed at r=0 again. This phenomenon could be explained by the impinged spray density distribution on the heated surface as shown in Fig. 4. At the spray height of 5 mm, most of the liquid or droplets are impinging on the surface centre thereby a measured temperature at r=0 is lower. As the spray height increases, a dilute spray density at the spray cone centre tends to create a higher $T_{r=0}$ under the spray height from 10 to 20 mm. At the spray height of 25 mm, a lower $T_{r=0}$ is obtained due to the higher spray density at the spray cone centre. From the experimental results in Figs. 4 and 5, it is expected that a uniform spray density distribution is favourable to achieve a uniform temperature distribution on the heated surface.

At the high applied heat flux of 64.5W/cm^2 as shown in Fig. 6, the surface temperature is observed to be higher at r=0 even with the impinged spray height of 25 mm. This could be attributed to the expanded spray cone under the high surface temperature in experiments. It is observed in the experiments that, the high surface temperature accelerate the liquid evaporation at the liquid film interface, from which a strong uprising vapour flow is generated to push the conical thin film and droplets to expand the spray cone. As discussed above, the expanded spray cone with larger spray angle requires a larger spray height to overlap the droplets at the spray cone centre. On this account, when the surface temperature is high, the peak droplet flux impingement may not occur at the surface centre due to the expanded spray cone even the spray height is 25 mm. From the surface temperature distributions, it could be inferred that the droplets impingement is the primary heat transfer mechanism in the-non boiling regime of spray cooling as suggested in the previous studies [8, 9].

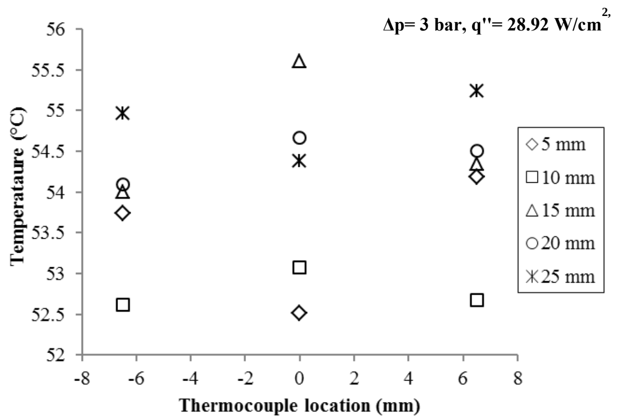


Fig. 5 Surface temperature distribution at Δp = 3 bar, q'' = 28.92 W/cm^2

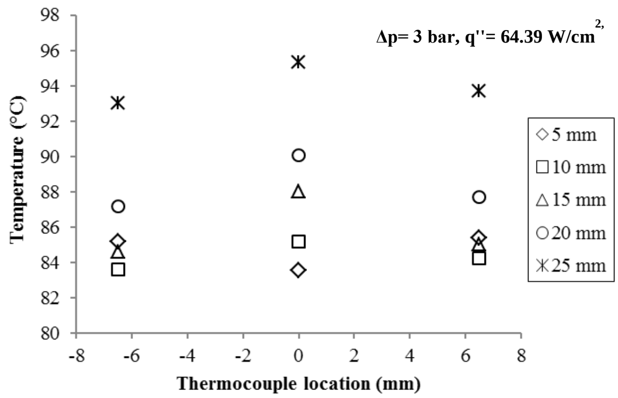


Fig. 6 Surface temperature distribution at Δp = 3 bar, q'' = 64.39 W/cm^2

3.3 Effects of spray height and pressure drop on heat transfer

As shown in Fig. 7, the pressure drop is observed to have positive effect on the heat transfer performance in spray cooling. It is reasonable that the higher pressure drop generally provides more impinging coolant on the heated surface thereby a lower surface temperature is achieved. For the spray height, the effect is more complex as it could introduce different droplet flux distributions and impact energy on the test surface. As shown in Fig. 7, a general trend is observed that the heat transfer coefficient decreases as the impinged spray height increases except at the low heat flux. At the heat flux around 28.92 W/cm^2, an optimal impinged spray height is found at around 10 mm to obtain the maximum heat transfer coefficient. It is suggested that, as the impinged spray height increases from 5 to 10 mm, the directly impinged surface area increases which tends to enhance the heat transfer performance. However, as the spray height increases continuously, the droplets impact energy reduces, which overcomes the positive effect of the increased impinged cooling area and consequently decreases the heat transfer coefficient. When the heat flux is larger than 64.39 W/cm^2, a high surface temperature is resulted and increases with the increasing of spray height. The impinging droplets have to overcome the uprising vapour flow before impinging on the heated surface, and along with the longer travel path at the higher impinged spray height, the heat transfer deteriorates as the spray height increases.

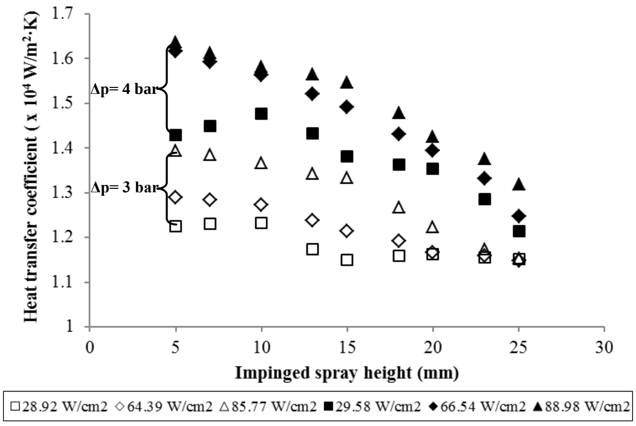


Fig. 7 Effect of impinged spray height on heat transfer coefficient: hollow symbol represents the results at $\Delta p = 3.0$ bar; solid symbol represents the results at $\Delta p = 4.0$ bar

4. Conclusions

In this study, the characterizations of a swirl nozzle on spray and heat transfer performances were investigated. The experimental results give a viewpoint of a swirl nozzle in a spray cooling application by adjusting different spray height and pressure drop.

For liquid atomization, the lower working pressure drop is preferred for the swirl nozzle to generate a full cone spray, while the higher pressure drop helps to generate finer droplets and larger spray angle. In heat transfer, the measured surface temperature distribution indicates that the droplets impingement is the primary cooling mechanism in the non-boiling regime of spray cooling, and the surface temperature affects the impinged spray cone and changes the droplet flux distribution when the droplets impinge on the test surface. Increasing the nozzle pressure drop can enhance the heat transfer performance in the non-boiling regime of spray cooling.

Acknowledgements

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