L	Test tube length, *m*
m'_{cv}	Evaporation rate, *kg/s*
m'_{wi}	Initial sprayed mass flow rate, *kg/s*
P_{spray}	Spray pressure, *bar*
q	Heat flux, kW/m^2
t_i	Sprayed water initial temperature, *K*
t_{leid}	Leidenfrost temperature, *K*
v_i	Droplet initial velocity, *m/s*
v_m	Droplet mean velocity, *m/s*
zz	Falling distance (vertical distance from the nozzles distributor to the test tube surface), *m*

Greek Letters

$\Delta t_{sup.}$	Superheating (the difference between the hot surface temperature and the formed vapor saturation temperature), *K*
$\Delta t_{sub.}$	Subcooling (the difference between the formed vapor saturation temperature and the sprayed water initial temperature), *K*
φ_n	nozzle angle, *deg.*

Subscripts

v	Vapor
w	Water
zz	Falling distance

Abbreviations

CR	Contact ratio (the ratio between the sprayed mass flow rate in-contact with the tube surface and all of the sprayed mass flow rate), -
HTE	Heat Transfer Effectiveness, the ratio between the evaporation rate and the initial sprayed mass flow rate, -
P/DPA	Phase / doppler particle analyzer.

1. Introduction

The impact of a droplet onto a hot solid surface is a fundamental phenomena in a variety of different applications such as spray cooling in nuclear reactors during loss of coolant accident, nuclear reactor primary circuit pressurizer spray control, spray cooling in flash evaporators, spray cooling in cryogenic applications, quenching, in iron and steel industry. The droplet spray distribution depends mainly on the nozzle configuration and the spraying pressure. The type of atomizer used to produce a spray-cooling scheme can vary widely. Selecting the correct liquid nozzle distribution is important for the spray characterization. The best distribution normally depends on the application and should be homogenous. Knowing the liquid distribution of a nozzle helps in achieving the best distribution (spacing) for applications with more than one nozzle. Bernardin et. al [1] studied mapping of impact and heat transfer regimes of water drops impinging on a polished surface by using still and high speed photographic techniques.

Heat transfer mechanisms of horizontal impacting sprays were studied experimentally by Choi and Yao [2]. The horizontal impacting sprays give a lower heat transfer at film boiling than the corresponding vertical sprays. The film boiling heat transfer is mainly controlled by the liquid mass flux. At low liquid mass flux and low droplet Weber number (ratio between the inertia force to the surface tension force), the heat transfer increases with the droplet Weber number. At high sprayed mass flux, the heat transfer is not significantly affected by the droplet Weber number. An experimental correlation for the hot transfer effectiveness in the region associated with film on film boiling heat transfer impacting sprays was obtained by Yao [3]. In his study the analyzing of the impacting sprays was classified into two cases: dilute spray (negligible heat transfer interaction among droplets) and dense spray (significant interaction).

Experimental water spray cooling of hot surfaces was studied by Mousa [4]. He investigated heat transfer characteristics below surface superheating temperature of 500 K and the effect of subcooling of sprayed water on the heat flux was also examined. An experimental correlation for the heat transfer effectiveness in the region associated with film boiling was obtained. Ito [5] investigated experimentally the heat transfer mechanism of fog cooling. He concluded that the evaporation heat transfer increases inversely with square root of the droplet diameter and droplet velocity and they also shown that the mass velocity and the surface superheating $\Delta t_{sup.}$ have a strong effect on the evaporation heat transfer.

Heat transfer experiments of mono-dispersed vertically impacting sprays were studied by Yao and Choi [6]. It was shown that at low liquid flux, the film boiling heat transfer of an impacting spray is affected by the droplet size and velocity; however, at high liquid flux these effects become much less observable. Holman and Mcginnis [7] studied experimentally heat transfer from inclined heat transfer surface to individual impinging water. They found that the peak values of the heat transfer per droplet occurred at surface superheating approximately 167 K. A general correlation for peak transfer per droplet was obtained.

The process of evaporation at atmospheric pressure of atomized water on hot surface was investigated experimentally by Bonacina et. al [8]. An empirical formula based on the experimental data was presented up to a maximum heat flux of 50 kW/m^2. They investigated that this correlation depends on a fraction of heat transfer area covered by droplets, mass mean diameter of liquid droplets and droplets thermal conductivity. Emmerson [9] studied experimentally the effects of pressure and surface material on evaporation of water droplets on horizontal hot surface. It was found that, as the pressure increases, the evaporation rate decreases and leidenfrost temperature increases.

Tewari et. al [10] studied the nucleate boiling in a thin film on a horizontal tube at atmospheric and sub-atmospheric pressures. They found that, the boiling heat transfer coefficient increases with increasing the sprayed mass flow rate for atmospheric and sub-atmospheric pressures in turbulent flow, and the boiling heat transfer coefficient decreases with a decrease in the saturation pressure. An empirical correlation is proposed to predict the boiling heat transfer coefficient based on the experimental data.

Awad et. al [11] investigated computationally the spray heat exchanger performance. The main objective of their study is directed towards the investigation of the boiling heat transfer coefficient and the evaporation rate for spray cooling on a horizontal tube evaporator. The present experimental study is directed towards investigating the effect of droplet size, droplet velocity, droplet density and the distance between the nozzle distributor and the tube surface on heat transfer coefficient and evaporation rate.

2. Experimental loop

A layout of test loop used in this work is shown in Fig. (1). This test loop consists of a circulating pump (15), primary heater (9), first electrical heater (10), second electrical heater (11), test chamber (3), condenser (7), electrical boiler (5) and condensate tank (6). The loop is equipped with necessary piping lines, valves, flow meters, pressure gauges and temperature gauges. Circulating pump is used to circulate the water through the loop. Water is primary heated, in the primary heater, by using the heat of evaporated vapor for increasing the water temperature and then, the water is passed to the first and second electrical heaters to increase its temperature nearest the saturation temperature corresponding to the pressure inside the test chamber to insure boiling of the sprayed water over the tube surface, this temperature is controlled by adjusting the electrical heaters. Then, water is passed to the nozzles distributor in the test chamber to spray over the outside surface of the test tube.

The test tube is heated by dry saturated steam, from the boiler (5), to obtain constant surface temperature during the experiments. The falling distance is adjusted by moving the distributor up and down along slots on the side walls of the test chamber.

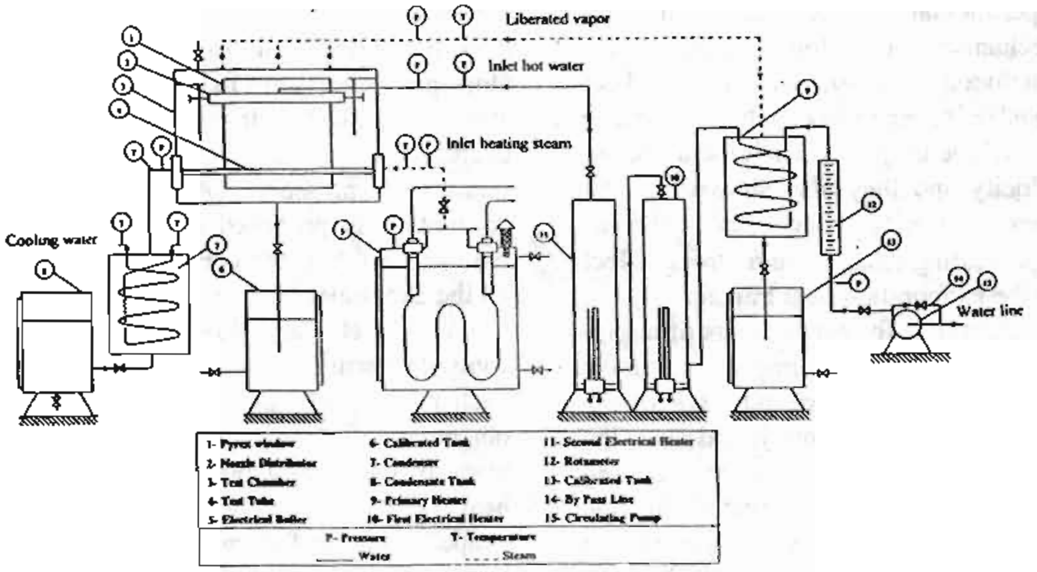


Fig. (1). Experimental test loop.

Heating steam leaves the test tube and enters the condenser, the mass flow rate of the heating steam is measured by collecting the condensate in a calibrated water tank (8). City water is used for the condensation process in the condenser. Liberated vapor from the test chamber is passed to the primary heater in which, this amount of evaporated vapor will be condensed, then accumulated in another calibrated water tank (13). Pressures, temperatures and mass flow rates of sprayed water, evaporated vapor, heating steam and the city cooling water are measured in different specified points in the test loop. Droplet size and its velocity are measured by using Aerometrics phase doppler particle analyzer (P/DPA). All parts of the experimental loop were good insulated by a layer of insulating glass wool coated by an aluminum sheath to reduce heat losses from the loop.

2.1 Test chamber

The test chamber used in the present experimental work simulates a single horizontal tube evaporator. It is manufactured from stainless steel with nominal dimensions of 60 x 70 x 48 cm and wall thickness of 2 mm, as shown in Fig. (2). There are two Pyrex windows of 35 x 35 cm for visual observation water spray. Water is sprayed onto the test chamber through the distributor nozzles at a temperature nearest the saturation temperature corresponding to the pressure inside the test chamber.

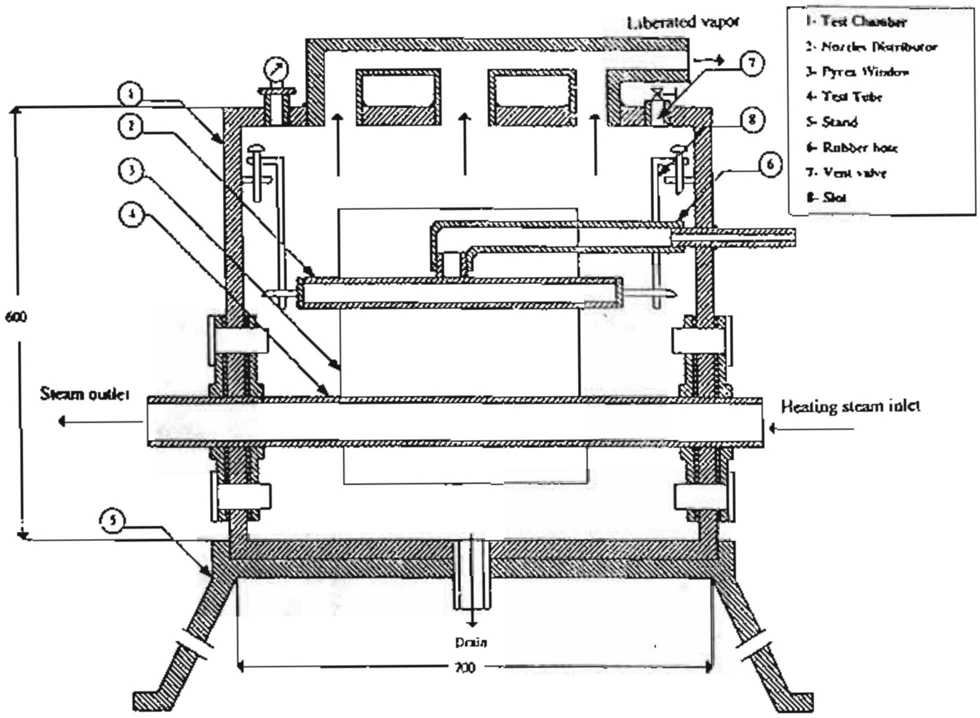
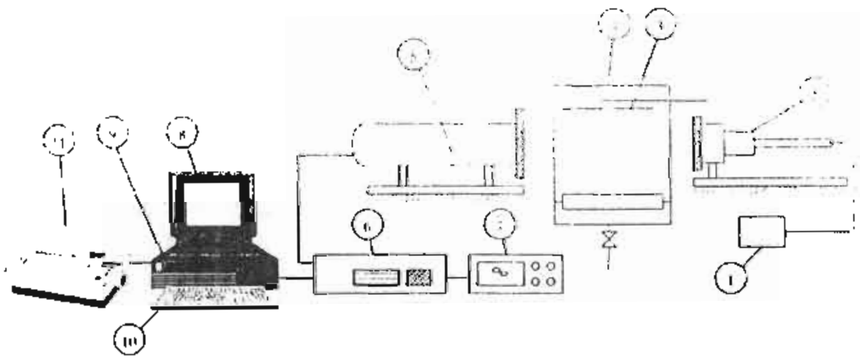


Fig. (2). Sectional view of the test chamber.



1. Exciting power supply
2. Laser beams transmitter
3. Nozzle distributor
4. Test chamber
5. Receiver
6. P/PDA signal processor
7. Oscilloscope
8. Monitor
9. Computer C. P. U
10. Key board
11. Printer

Fig. (3). Schematic diagram of the phase Doppler particle analyzer, (P/DPA).

The distributor is a steel tube of 50 mm outside diameter, 48 mm inside diameter and 500 mm length. Water is sprayed on the outer surface of the heated test tube through three nozzles with 0.8 mm diameter and the nozzle's configuration angle is 50° at 10 bar sprayed liquid pressure, so by using three nozzles there is no interaction between the droplets coming from the different nozzles at different values of falling distance. The test chamber is equipped with a pressure gauge to measure evaporation pressure. Also, test chamber is provided with a vent valve to insure that there are no air and dissolved gases inside this chamber. Test tube is made of copper with 25.4 mm outside diameter, 23.4 mm inside diameter and 500 mm length.

The droplet velocity and its size were measured by using the aerometric phase/ Doppler particle analyzer (P/DPA), as shown in Fig. (3), which utilizes the light scattering from two laser beams, at its intersection point, by spherical particles to obtain a simultaneous size and velocity measurements for individual particles.

3.Results and discussions

3.1. Effect of radial distance from the spray centerline on the formed droplet velocity and diameter

Figure (4) illustrates the effect of the radial distance from the nozzle centerline on (a) droplet sauter mean diameter (d_{32}), (b) droplet mass mean diameter (d_{30}) and (c) droplet mean velocity (v_m) at falling distance, ZZ, of 20 cm and at different spray pressures, p_{spray}, of 6 and 9 bar.

From figures (4a) and (4b) respectively, it can be seen that, the sauter mean diameter and the mass mean diameter has a minimum values at the centerline and increases monotonically towards the spray periphery. This is due to the great effect of the inertia force at the spray centerline and the effect of the drag force at the spray periphery. So, the droplet size will increase by increasing the radial distance from the spray centerline. From figure (4c) that, it can be seen that, the droplet mean velocity has a maximum value at the spray centerline, and decreases towards the edge of the spray due to the effect of the inertia force at the spray centerline and the great effect of the drag force of the surrounding medium at the spray periphery. So, the droplets mean velocity will decrease by increasing the radial distance from the spray centerline.

3.2 Effect of the falling distance on the evaporation rate and the heat transfer effectiveness

To study the effect of the falling distance (ZZ) on the evaporation rate and the heat transfer effectiveness experimentally, a two different experimental runs have been carried out. The working conditions for these two runs are given in table (1).

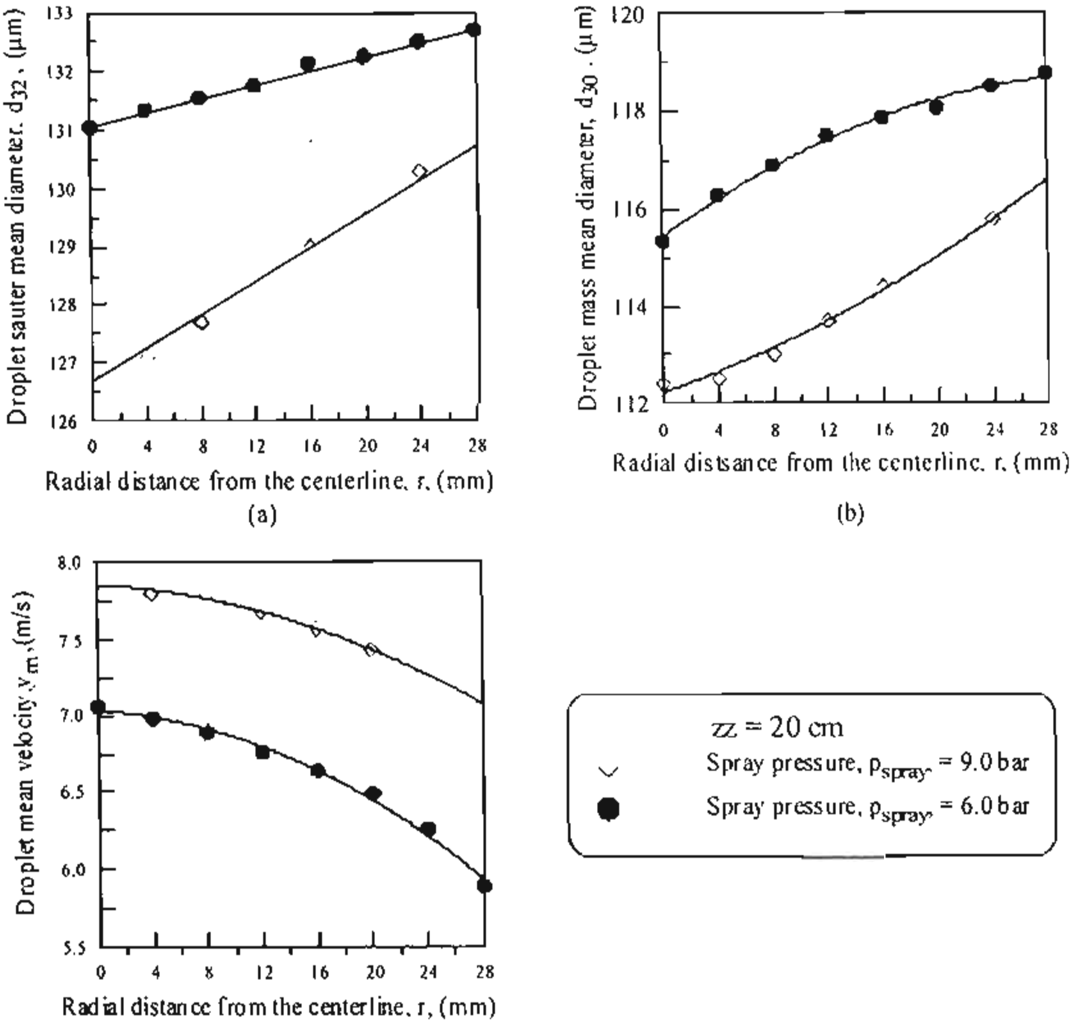
Figure (5) illustrate the effect of the falling distance on (a) evaporation rate, (b) heat transfer effectiveness and (c) heat flux. From the figure, it can be seen that, the evaporation rate, the heat transfer effectiveness and the heat flux decrease by increasing the falling distance, and it can also be seen that, the spray pressure has a small effect on these parameters. Generally these parameters are slightly decreased by increasing the spray pressure.

3.3 Comparison between the present experimental results and theoretical results for the evaporation rate

Figure (6) illustrates a comparison between the present experimental results and the theoretical ones [(ref. (11)] for the evaporation rate (m'_{ev}) for the two experimental cases. From the figure, it can be seen that, for the low values of the falling distance, the evaporation rate is high and vice versa for the high values of the falling distance, the evaporation rate is low. This is true for both experimental and theoretical studies. That is because of decreasing the contact ratio CR by increasing the falling distance ZZ with this type of nozzle configuration (φ_n=50 deg.).

Run	p_{spray} bar	v_l m/s	d_l μm	m_{wl} g/s	Δt_{sub} °C	p_l bar	Δt_{sup} °C	ϕ_n deg.
1	6	6.64	132.9	55.6	10	1.0	40	50
2	9	7.43	128.4	61.1	10	1.0	40	50

Table (1). Experimental working conditions



(c)

Fig. (4). Change of: a) droplet sauter mean diameter, b) droplet mass mean diameter and c) droplet mean velocity with the change of radial distance from the centerline of the nozzle at different values of the spray pressure.

It can also be seen that, the evaporation rate for the first case is higher than that for the second case. This is because; the waiting time, the mean lifetime of the droplets falling onto the hot surface, and the transmitted heat per one droplet for the first case are higher than that for the second case. Comparing the experimental results with the theoretical ones, gives that, the theoretical values are higher than the experimental ones. That is due to the heat losses in the experimental work and the simplified assumptions taken in the theoretical model. And it can also be seen that, this difference decreased by increasing the falling distance. That is because, for the low falling distance the temperature difference between the sprayed droplet and the formed vapor is high, thus, the vapor condensation rate on the droplet surface is high; therefore the experimental value (evaporation rate) will decrease. The difference between these results is ranged from 8 to 12 %.

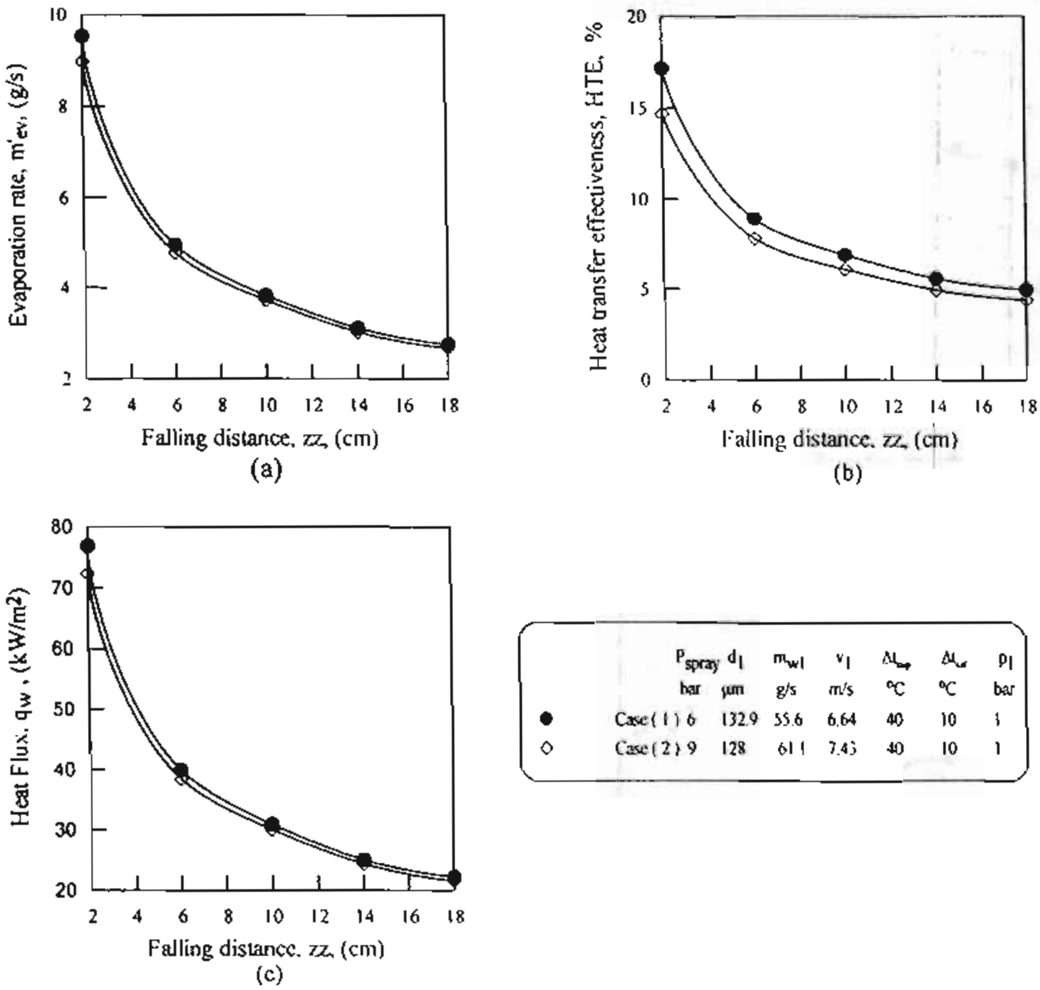


Fig. (5). Experimental results for the effect of the falling distance on the: a)evaporation rate, b) Heat transfer effectiveness and c) Heat flux.

3.4 Comparison between the present experimental results and theoretical results due to others for the heat flux

Figure (7) illustrates the comparison between the present experimental results and theoretical ones of ref. [11] for the heat flux. From the figure, it can be seen that, for the low values of the falling distance, the heat flux is high and vice versa for high values of the falling distance, the heat flux is small. That is because, the number of droplets in contact with tube surface decreases by increasing the falling distance as was mentioned above. By comparing between the theoretical and experimental results, it can also be seen that, the difference between them is ranged from 8 to 12 %. That is due to the heat losses to the environment.

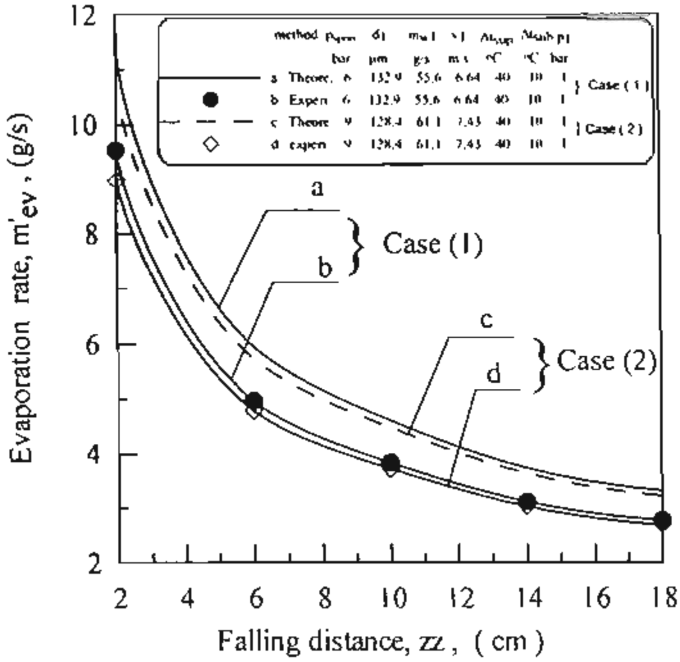


Fig. (6). Comparison between the present experimental results and theoretical results of ref. [11] for the evaporation rate.

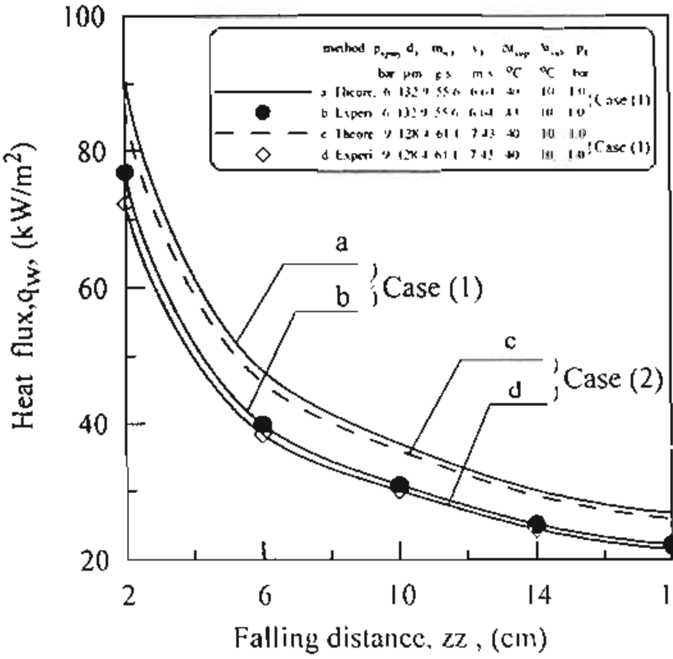


Fig. (7). Comparison between the present experimental results and theoretical results of ref. [11] for the heat flux.

4. Conclusions and Recommendations

From this study, it can be concluded that, the experimental and computational model results are in good agreement for the prediction of evaporation rate, heat transfer effectiveness and heat flux. For both avenues, the droplet impinging velocity and the sprayed mass flow rate increase as spray pressure increases. By increasing the radial distance from the spray centerline, the droplet velocity decreases where the droplet size is increased. Increasing the falling distance, evaporation rate, heat transfer effectiveness and heat flux are decreased. It is recommended, in future studies, to examine the effect of falling distance on the spray cooling characteristics using a different layout of tube bundles. A variety of nozzle pressure and configurations are essential to investigate their effects on the evaporation rate and heat transfer effectiveness.

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