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Heat transfer enhancement by jet impingement on dimpled surface with different cavities

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Abstract*—Jet impingement is a cooling technique, widely used where the high rate of heat transfer are required. It is very ease to implement. Dimples have simple geometry, light weight, low maintenance, low pressure penalty and it promotes turbulent mixing due to which the boundary layer get thinned and partially breaks which leads to heat transfer augmentation. The process of jet impingement is to incident the high velocity air jet coming from the nozzle on a target surface having dimples of various geometry. It is used for cooling, heating and drying purposes like in hot metal cooling, turbine blades cooling and in cooling electronics equipments etc. This study will investigate the effect of jet impingement on a target surface with a dimple pattern. Also the effect of various Reynolds number, H/D ratios and different shapes of cavities on the heat transfer rate by jet impingement is investigated. Spherical, cylindrical and rectangular cavities were used within a range of Re=10000-30000. The H/D ratio changes from 2, 4, 6, 8. Finally all the results were compared with that of flat plate. It was found that the dimple plate with spherical cavity shows best result compared to all other plates.

Keywords: **Jet impingement, Dimple Surface, Turbulent Flow**

I. INTRODUCTION

Jet impingement is a cooling technique, widely used where the high rate of heat transfer are required. Also it is very ease to implement. Jet impingement is used for cooling, heating and drying purposes. Typical applications include cooling turbine blades and electrical equipments, drying of textiles and other wetted surfaces, and heating or cooling of metal plates. As these applications require heating and cooling to be at the maximum speed possible to maintain efficiency, it follow that the use of a process such as jet impingement is a viable option. Jet impingement is an attractive cooling mechanism due to the capability of achieving high heat transfer rate. Impinging jet is used in many engineering applications to enhance heat transfer for cooling or heating purpose or mass transfer for vapour deposition. In gas turbine, the temperature reaches to 2000°C at the inner wall of leading edge region of blades and outer wall of combustors i.e. for every rise in 55.5°C increase in temperature, the work output increases approximately 10% and it gives 1.5% increase in thermal efficiency. Therefore it is very essential to maintain the high rates of heat transfer for high efficiency and performance.[5] To increase the rate of heat transfer, surfaces are modified with fins, cavities, vortex generators and dimples. Dimples are used on target surface of jet impingement to enhance the heat transfer rate. Dimples have simple geometry, light weight, low maintenance, low pressure penalty and it promotes turbulent mixing due to which the boundary layer get thinned and partially breaks which leads to heat transfer augmentation. The factors which influence the heat transfer by jet impingement includes nozzle geometry, jet to plate distance, jet incidence angle, radial distance from stagnation point, crossflow scheme, Reynolds number and Nusselt number. Kanokjaruvijit et.al.[1] performed an experiment on an eight-by-eight jet array impinging onto a staggered array of dimples of hemispherical and cusped elliptical shape at Reynolds number 11,500. The jet to plate distance was adjusted to be 2, 4 and 8 jet. It had been concluded that jet impingement onto dimples performed best with the maximum crossflow scheme and larger jet-to-plate spacing due to the coupled effect of impingement and channel flow. Xing et.al.[2] performed an experiment on nine-by-nine jet array impinging on a flat and dimpled plate at Reynolds numbers from 15,000 to 35,000. The distance between the impingement plate and target plate was adjusted to be 3, 4 and 5 jet diameters. The jet-to plate spacing (H/D = 3) was better than the others either on the flat or dimpled target plate. The heat transfer performance on the dimpled plate was always better for the minimum crossflow for different jet-to-plate spacing. The heat transfer enhancement ratio increases with increasing Reynolds numbers. The narrow jet-to-plate spacing H/D = 3 results in the highest heat transfer enhancement for different crossflow schemes. The highest enhancement ratio was up to 12.3%. The discharge coefficients of the impingement plate and exit rims were similar for different arrangements.

II. EXPERIMENTAL WORK

Experimental work is done on the setup as shown in the fig.1. In the air flow bench the pipe was used to connect the blower outlet to acrylic duct to carry the forced air from blower to the duct. Next to the blower outlet, flow regulating valve was used, connected to the pipe to regulate the air flow. Orifice meter was introduced next to the regulating valve to measure the regulated air flow rate in the pipe. Water manometer was connected across the orifice meter. Water manometer showed the pressure differential across the orifice meter in centimeters of water column difference. Duct was connected to air flow bench to force the air vertically on the test plate. The heater plate was fixed at the bottom of the test plate, was connected to the power socket through dimmerstat. Dimmerstat readings were kept constant at 100 W to give the heat input to the heater. Caliberated Copper Constantan thermocouple (T-type) wires were used to measure the temperature at various locations on test plate and the air exit temperature. Provision was made to fix the thermocouple junction at the test plate. Digital temperature indicator used to show the temperature readings. Following fig.1. shows the

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schematic diagram of actual test set up. Thermocouple wires were connected to corresponding channels of temperature indicators and the four drilled holes of the test plates. Two thermo couple were connected to the inlet and exit for measuring the inlet air and spent air temperature respectively.

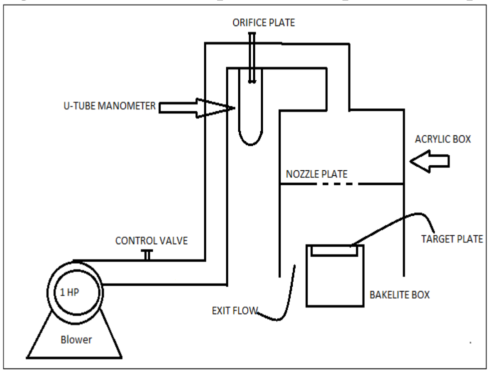

Fig.1: Schematic diagram of experimental setup.

The aluminium plate was heated by a plate type heater of 200W. The wattage was maintained at 100W. The blower also get started at minimum Re=10000 by maintaining the h_w = 9mm in the manometer. It was found that nearly 2.5-3 hours were required to attain the steady state condition. As the steady state was attained, the values of four points at four sides of the plate connected with a thermocouple showed the temperature on temperature indicator. One thermocouple was connected at the exit of the spent air. Thus there were five temperature readings indicated on the control panel. Now by changing the Re value by adjusting the valve and maintaining the h_w = 1.7 cm, nearly 30 min would require for attaining the steady state. And then again take all five temperature readings. Repeat the same procedure for Re = 15000, 20000, 25000, 30000. All these readings were taken at H/D=2. Repeat the same procedure for H/D = 4, 6, 8 and with different cavities. All plates had dimension as 120 x 120 x 10 mm^3 with 4 x 4 array of dimples. Now to maintain the equal surface area for heat transfer, the depth of all three cavities was kept constant at 4mm. The diameter of spherical dimple cavity was kept at 20mm which gives the surface area of the plate 364.42 mm^2. Now to maintain the equal surface area, the diameter of cylindrical cavity was kept at 15 mm and the length of the rectangular cavity was 12.7 mm. Thus equal surface area of cavities was maintained on all three plates.

III. DATA REDUCTION

Reynolds number was calculated from the formula as

$Re = \rho v D/\mu$

Mass flow rate of the coming out from the nozzle plate can be calculated from the formula as

$$m_a = \rho A v \qquad \& \qquad m_a = C_d \times \frac{\pi}{4} \times d_o{}^2 \times \rho_a \times \sqrt{\frac{2\times g\times h_a}{1-\beta^4}}$$

Height in the water column which is to be maintained for above Reynolds number can be calculated by

$\mathbf{h_w = h_a \times \rho_a / \rho_w}$

Bulk mean temperature can be calculated as

$\mathbf{T_{bmt} = (T_{ain} + T_{ao})/2}$

Heat Consume

$\mathbf{Q = m\, C_p\, (T_{ao} - T_{ain})}$

Heat transfer coefficient

$\mathbf{h = Q / A\, (T_s - T_{bmt})}$

Nusselt Number

$\mathbf{Nu = hl / K_{bmt}}$

IV. RESULT AND DISCUSSIONS

The sample experimental results are presented in the graphical form in the following graphs. Fig.2 shows that at H/D=2, dimple plate has highest Nusselt number. It is due to the fact that dimple plate has more surface area than flat plate and also due to the shape of dimple more turbulence get generated which leads to more mixing of fluid. In case of rectangular cavity dimple, the flow gets trapped inside the cavity preventing the incoming flow to enter. It is due to the small distance between the nozzle plate and test surface. Fig.2 also shows the variation of Nusselt number with Reynolds number at H/D =4. This graph shows Nusselt number is maximum during the project work for spherical dimple plate. Because at H/D=4 spent flow has enough passage to exit from the cavity which leads to highest Nusselt number while in case of cylindrical cavity little amount of flow get trapped in the cavity but still it shows a better Nusselt number than rectangular cavity and flat plate. Here rectangular plate shows higher Nusselt number than flat because it has more surface area than flat plate and the flow has enough passage to exit.

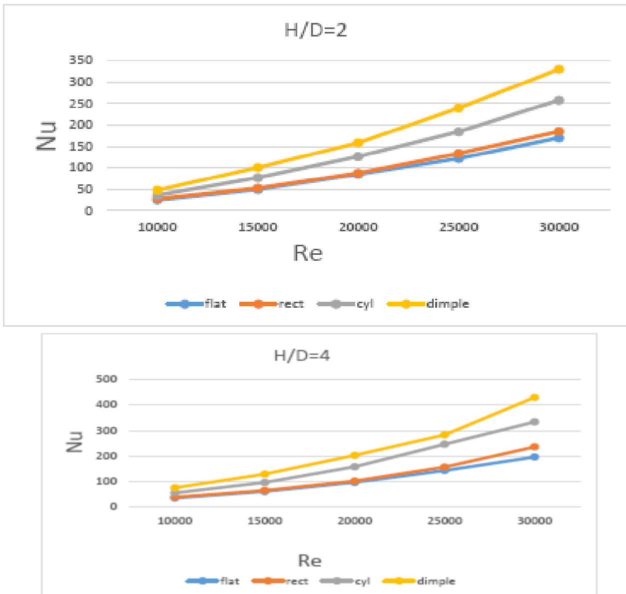

Fig.2: Variation of Nu vs Re at H/D=2 & H/D=4

Fig.3 shows the variation of Nusselt number with Reynolds number at H/D=6. It shows the same pattern of results as that at H/D=4 but little drop in Nusselt number. It is due to, at H/D=6 the jet coming from nozzle plate loose its confinement and get splits which leads to mixing of two adjacent jets. This loosening of sharpness of jet affects the heat transfer rate. Hence it shows lesser Nusselt number than at H/D=4. Fig.3

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also shows the variation of Nusselt number with Reynolds number at H/D=8. At this distance, the graph shows the same pattern as that at H/D=4, 6. But the large distance of jet travel affects the heat transfer rate. Confinement of jet get disturbed due to this long distance. It also leads to the mixing of adjoining jets which loses its sharpness. Thus less heat transfer rate is recorded than that at H/D=2, 4, 6. Fig.4 shows the graph between the Nusselt number ratio of cavity plates with that of flat plate vs. Re at H/D=2. It shows that the Nu ratio is maximum for the plate with dimple cavity than cylindrical cavity and rectangular cavity. It means that there is more heat transfer rate on dimple plate than at cylindrical plate and rectangular plate.

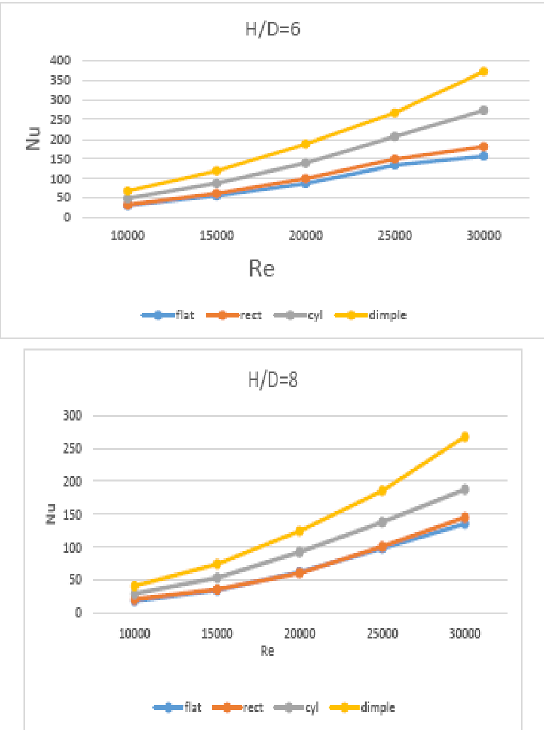

Fig.3: Variation of Nu vs Re at H/D=6 & H/D=8

Fig.4 also shows the graph between the Nusselt number ratio of cavity plates with that of flat plate vs. Re at H/D=4. This graph shows the maximum Nu ratio in overall project. This is due to the reason that at H/D=4 the action of jet is very confined and there is no mixing of adjacent jets which leads to highest heat transfer rate. Also the shape of dimples plays an important role in augmentation of heat transfer. Dimple cavity shows highest heat transfer rate than all other plates and cylindrical cavity shows better results than rectangular cavity. Fig.5 shows the graph between the Nusselt number ratio of cavity plates with that of flat plate vs. Re at H/D=6. At H/D=6, Nu ratio is better than at H/D=2 but lesser than H/D=4. It is because disturbance in confinement and mixing of jets. Maximum Nu ratio is found to 2.4 for dimple plate at Re=30000.

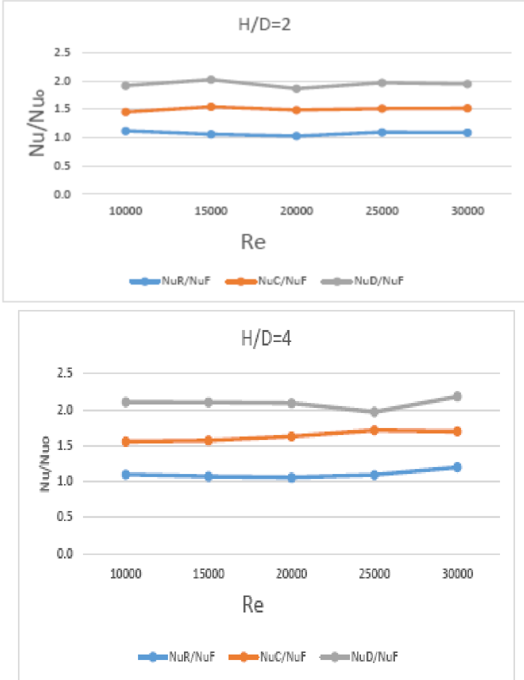

Fig.4: Graph between Nu/Nuo vs. Re at H/D=2 & H/D=4

Fig.5 also shows the graph between the Nusselt number ratio of cavity plates with that of flat plate vs. Re at H/D=8. At H/D=8, Nu ratio shows worst performance compare to all other H/D ratios. It is because the air jet has to travel long distance which disturbs its confinement. This unconfined jet mixes with other adjoining jets leading to the poor heat transfer rate. The highest Nu ratio is 1.7 for Re=30000 on dimple plate and the lowest is 1.2 for rectangular cavity plate at Re=10000.

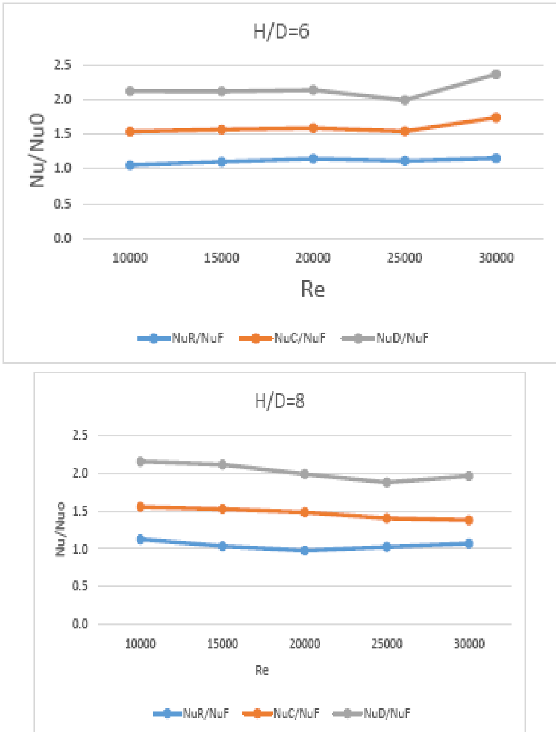

Fig.5: Graph between Nu/Nuo vs. Re at H/D=6 & H/D=8

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V. CONCLUSION

This experiment was carried for investigating the effects of different cavities on heat transfer by jet impingement on dimples surface. Main conclusions are summarized as

1) Use of dimples increases the rate of heat transfer compare to that of flat plate.
2) Heat transfer rate increases with increase in the mass flow rate.
3) Use of dimples augment the heat transfer rate with lesser pressure penalty.
4) Spherical cavity dimple plate augment highest heat transfer rate than cylindrical and rectangular cavity plate and flat plate.
5) Sharp edges of rectangular cavity trapped the flow preventing the passage for exit of spent air. Thus incoming air has no room to touch the surface of plate which leads to poor heat transfer rate.
6) Nusselt number is maximum for dimple plate with spherical cavity at Reynolds number 30000. It was found to be 430 at H/D=4.
7) Distance between nozzle plate and test plate also affects the rate of heat transfer. At H/D=2, flow got trapped in between the nozzle plate and test plate while at H/D=4 there is highest augmentation in heat transfer. Whereas at H/D=8, jet loses its confinement and mixes with adjoining jets leads to the poor heat transfer rate.
8) Dimple cavity reduces the weight of the plate. The weight of dimple and cylindrical cavity plate was found to be 372 gm. and rectangular plate was 390 gm. compared to that of flat plate 416 gm.

VI. FUTURE SCOPE

1) In this project work, experiments were carried for investigation of heat transfer by jet impingement on dimpled surface with different cavities. All readings are taken at Reynolds number between 10000-30000. It can be extended for higher Re range.
2) The material used for test plate was aluminium. It can be change to steel or any other suitable material according to its application.
3) Different shapes of dimple cavity like triangular, leaf shape, tear drop shape etc. can be used.
4) In this project work vertical jet was used for impingement. The angle of impinging jet can also be vary for experimentation.

Nomenclature

Re	Reynolds Number
Nu	Nusselt Number
H	nozzle to plate distance, mm
D	Diameter of nozzle, mm
W	Watt
h_w	Height in water column, mm
ºC	Degree celcius
ρ	Density, kg/m^3
µ	Dynamic viscosity, Ns/m^2
v	Velocity, m/s
bmt	Bulk mean temperature ºC
C_d	Drag coefficient

Subscripts

a_o	Air exit
a_{in}	Inlet air
o	orifice
a	air
w	water

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