Proceedings of the 9th World Congress on Mechanical, Chemical, and Material Engineering (MCM'23)
Brunel University, London, United Kingdom –August 06-08, 2023
Paper No. HTFF 203
DOI: 10.11159/htff23.203

Investigation Of Porous Carbon Foamed Surface Under A Circular Air Jet Impingement For Uniform Heat Transfer

Ketan Yogi[1], Anuj Kumar[1], Shankar Krishnan[1], S. V. Prabhu[1]
[1]Indian Institute of Technology Bombay
Powai, Mumbai, Maharashtra, INDIA
ketanyogi@iitb.ac.in, anujkumarshaw@iitb,ac.in, kshankar@iitb.ac.in, svprabhu@iitb.ac.in

Abstract **–** Impinging jets are widely adopted for applications that require high heat transfer rates. The major disadvantage of jet impingement heat transfer is non-uniformity in the heat transfer from the impingement surface. The present study investigates the targeted surface with attached and detached porous carbon foam under circular air jet impingement. Experiments are performed to measure the local temperature of the targeted plate using the thin metal foil technique and IR thermography. A carbon foam having 8 mm height and 85% porosity is used. The results of the targeted surface with porous carbon foam are compared with the targeted surface without foam for Nusselt number and coefficient of variance (*COV*). The Reynolds number and distance between targeted surfaces and nozzle exit are the varying parameters. The local Nusselt number of a targeted surface with carbon foam drops in comparison with the smooth surface. However, the carbon foam on a targeted surface offers more uniform heat transfer. The average Nusselt number and the *COV* of a targeted surface with carbon foam drop with an increase in the distance between the targeted surface and nozzle exit. A comparison of the heat transfer of the targeted surface with an attached and detached carbon foam suggests that the carbon foam pasted on the targeted surface offers conduction heat transfer. The conduction heat transfer offered by the foam is responsible for the uniformity in the heat transfer

Keywords**:** Jet impingement, porous carbon foam, IR thermal imaging, coefficient of variance, local Nusselt number

Nomenclatures :

Symbol	Meaning
d	Diameter of the nozzle (m)
h	Distance between targeted surface and nozzle exit (m)
h_{foam}	Height of the carbon foam (mm)
h_{local}	Local heat transfer coefficient (W/m^2.K)
k_{air}	Thermal conductivity of air (W/mK)
$\dot{m}$	Mass flow rate (kg/s)
q''_{conv}	Convective heat flux (W/m^2)
T_J	Jet exit temperature (K)
T_W	Temperature of the flat plate (K)
x	Horizontal distance from the collision point (m)
Greek Symbols	
ρ	Density of air (kg/m^3)
μ	Dynamic viscosity of air (Pa.s)
ε	Porosity (pore cross-sectional area/total cross-sectional area)

Dimensionless Numbers

Nu	Local Nusselt number
Nu_{avg}	Average Nusselt number
Re_d	Reynolds Number based on nozzle diameter
COV	Coefficient of variance

1. Introduction

The heat transfer using impinging jets is highly satiable for the high heat flux applications such as electronics cooling, the cooling of gas turbine components, rocket launcher cooling, cryosurgery, drying of textiles products and paper, glass tempering, metals cooling, etc. The heat transfer with jet impingement comprises a high-velocity jet of fluid passing from a hole or a slot that impinges on the surface to be cooled or heated. Jet impingement cooling offers better local heat transfer performance compared to parallel flow cooling such as duct flow due to the formation of a thin boundary layer on the targeted surface [1]. In the past decades, many studies reported the fluid flow and heat transfer characteristics of a surface under the impinging jet. Some of the studies report the enhancement of the heat transfer performance from a flat plate under the jet impingement condition. Recently, many researchers found that open-cell metal foams on a targeted surface under different impinging jet conditions enhance heat transfer [2 – 10].

An open-cell metal foam is a porous structure containing a solid metal with gas-filled pores covering a large portion of the volume. Although metal foams are lightweight, they have high strength and rigidity. Metal foam offers high surface area density, high permeability and high conductivity attracting researchers for thermal fluid applications. A detailed literature review on an experimental investigation of heat transfer characteristics of a circular air jet impingement on metal foam is reported by Yogi *et al.* [11].

The heat transfer is maximum at the impingement region and it sharply decreases in the direction away from the impingement point resulting in the nonuniform transfer of heat. The non-uniformity in the heat transfer from the surface under jet impingement major drawback. There are several applications in which uniform heat transfer from the surface is essential. No literature commented on the uniformity of the heat transfer from a targeted plate under jet impingement. Also, the modes of heat transfer in a porous foamed surface under jet impingement are not reported in the literature extensively. Hence, the present study investigates a porous carbon foamed surface under single circular air jet impingement for local heat transfer and uniformity of heat transfer from the targeted surface. The effect of the Reynolds number, the distance between targeted surfaces and nozzle exit, the height of the carbon foam on the local heat transfer and the uniformity of the heat transfer are investigated in this study experimentally. The objectives of the present work are as follows

- Measure the local temperature distribution for a targeted plate with (attached and detached) and without porous carbon foam under circular air jet impingement
- Compute the coefficient of variance (*COV*) for the targeted surface for uniformity in the heat transfer
- Investigate the effect of the Reynolds number and distance between the targeted surface to nozzle exit on the Nusselt number and *COV*.

2. Experimental setup and methodology

The experimental setup shown in Fig 1(a) used for the present study is adopted to form the study of Yogi *et al.*[28] An air jet exiting from the tube nozzle is made to impinge on a targeted surface. A thin stainless steel foil with 0.06 mm thickness is heated with electric (AC) power which is act as a targeted plate for impingement. The orifice meter is used to measure the air mass flow rate. The temperature of an air jet and the targeted surface is measured with a K-type thermocouple and IR camera respectively. More details of the experimental setup are mentioned in Yogi *et al.*[11].

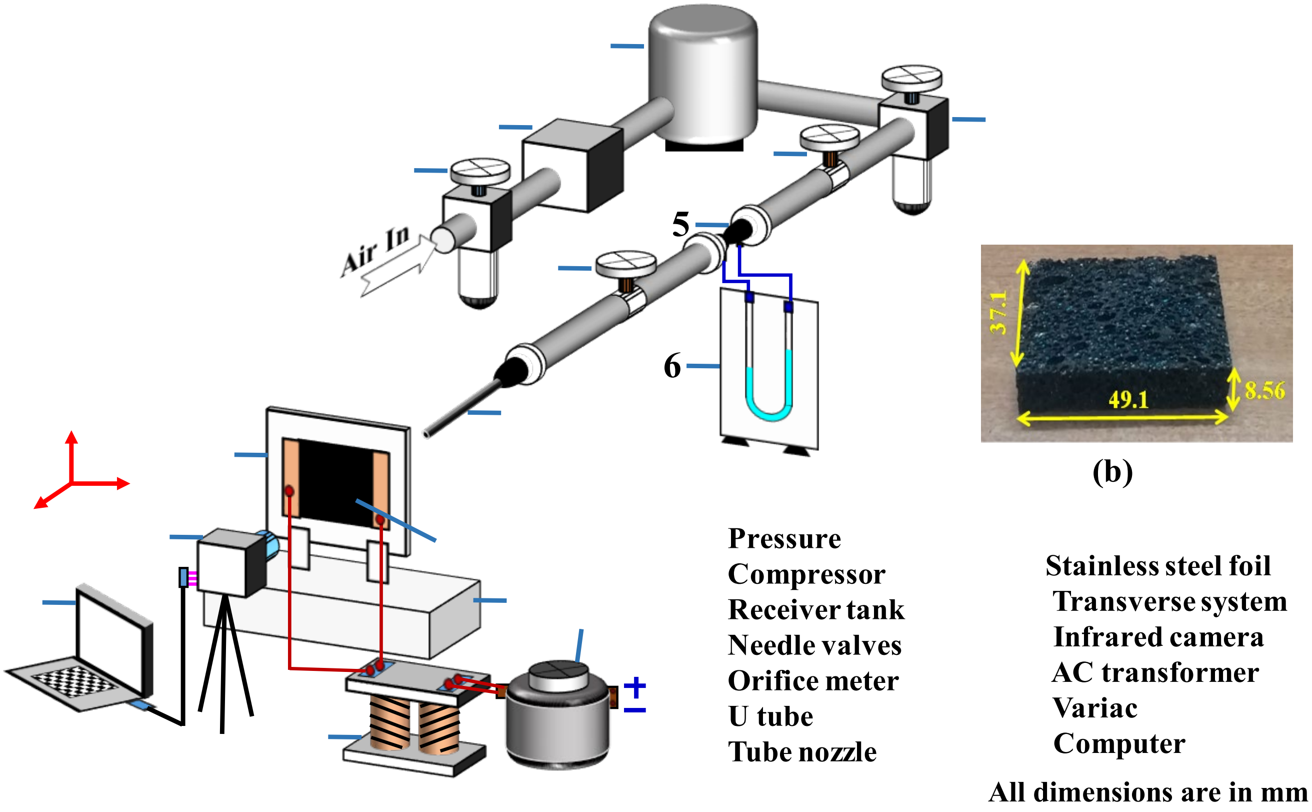

Fig. 1: Pictorial illustration of the experimental setup

Experiments are conducted for different distances between targeted surfaces and nozzle exit (h/d = 2, 4, 6, 8, 10) and Reynolds number (Re_d = 10000, 15000, 20000 and 25000). It is varied with the traverse system as shown in Fig.1. A porous carbon foam having 85% porosity and 8 mm height is shown in Fig 1(b). The method suggested by Yogi *et al.* [12] is adopted for pasting foam on targeted plate in attached and detached conditions.

The volumetric heat generated the targeted tinfoil due to electric heating. Most of the heat is convicted by the jet fluid and the rest heat is lost in the environment by radiation and natural convection. Heat loss experiments are performed separately as the method reported by Yogi *et al.* [11]. Using convection heat flux, the convective heat transfer coefficient is computed using Eqs. (1). The Nusselt number is computed using Eqs. (2). The measured mass flow rate is nondimetionlzed to get the flow Reynolds number as presented in Eqs. (3).

$$h_{local} = \frac{q''_{conv}}{(T_w - T_J)} \tag{1}$$

$$Nu = \frac{hd}{k_{air}} \tag{2}$$

$$Re_d = \frac{4\dot{m}}{\pi\mu d} \tag{3}$$

The method suggested by Moffat [13] is adopted to compute the experimental uncertainty. The uncertainties in the geometrical parameters of the test section are obtained by measuring the values at different locations. The average uncertainty of the flow Reynolds number measurement is 5.6 %. An average uncertainty in temperature measurement is 2.0 % and 2.5 % with K-type thermocouple and IR camera respectively. An uncertainty of 10.5 % is obtained in heat flux measurement.

The uncertainty is Nusselt number is calculated statistically from individual uncertainties of the experimental parameters and found to be 13.9 %.

3. Results and discussion

Experiments are conducted to measure the local heat transfer of a targeted surface (attached and detached) and without porous carbon foam under a single circular air jet. A porous carbon foam having 85% porosity and 8 mm height is used for the study. The IR imaging technique is used for the local temperature of the targeted plat. The Reynolds number varies between 10000 to 25000. The different distance between targeted surfaces and nozzle exit varies between 2 to 10. The experimental results are discussed in the following section in detail.

3.1 local Nusselt number (Nu_{local})

Figure 2 shows the variation of the Nu_{local} in a horizontal direction (x) for the case of the targeted surface with (attached and detached) and without foam for h/d of 4 and different Reynolds numbers. The Nu_{local} of the targeted surface without foam is maximum at the point of the collision/ impingement/ stagnation of the jet ($x/d = 0$). The Nu_{local} drops sharply in a direction away from the collision point and again rises to make a secondary peak around x/d of 2. The magnitude of the secondary peak is influenced by the jet Reynolds number as shown in Fig. 2. Beyond the secondary peak, Nu_{local} again drops in the direction away from the collision point. Hence, a non-uniform Nu_{local} profile is witnessed for the targeted surface without foam under single circular jet impingement. The results for a targeted surface without foam under air jet impingement is inline with the data reported in the literature [14].

The porous carbon foam covers the region till x/d of 3.5. Unlike the targeted surface without foam, the Nu_{local} remains unchanged within the x/d of 3. Beyond x/d of 3, the Nu_{local} drops sharply in the direction away from the collision point till x/d of 4. The Nu_{local} increases till x/d of 5.5. When the jet impinges on the target surface with porous metal foam, the jet experience additional resistance due to the presence of the foam. Hence due to the high momentum of the jet, a portion of the jet flow penetrates the foam and reaches the heater plate. The rest of the jet flow bypass from the top of the foam. After bypassing from the tip of the foam, this bypass flow comes in contact with the targeted plate near at x/d of 4. Hence the Nu_{local} again starts rising till x/d around 6.0. Beyond x/d of 6.0, the Nu_{local} drops as the jet loses momentum in the direction away from the collision point. The Nu_{local} for a targeted plate with attached foam shows lower Nu_{local} at all the x/d locations in comparison with the targeted surface without foam. However, the Nu_{local} is more uniform for the targeted surface with attached metal foam under jet impingement conditions which are uncommon.

The variation of the Nu_{local} for a targeted surface with detached foam follows a similar pattern as the targeted surface without foam till x/d of 4. Beyond x/d of 4, the Nu_{local} of a targeted surface with detached metal foam rises till x/d of 6.0 similar to the targeted plate with attached foam case. The Nu_{local} for a detached foam is consistently lower than the other two configurations studied here. The heat is transferred by means of convection offered by the jet fluid in the case of the targeted plate without foam and the targeted plate with detached foam. The comparison of the Nu_{local} of the targeted surface with detached foam and the targeted surface without foam suggests that the presence of the foam on a targeted plate drops the convection heat transfer offered by the jet fluid. The comparison with the targeted plate with detached foam and attached foam suggests that along with the convection offered by the jet flow, heat is also transferred by the condition offered by the foam in the case of the attached foam case. This can also validate by the fact that the Nu_{local} for a targeted surface with attached and detached foam matches beyond x/d of 4, where foam is not present. The conduction offered by the carbon foam makes heat transfer more uniform in comparison to the targeted surface without foam.

3.2 Average Nusselt number (Nu_{avg}) and coefficient of variance (*COV*)

The Nu_{local} is averaged for the region of the x/d of 0 to 3.4 (region covered by porous foam) to get the Nu_{avg}. The variation of the Nu_{avg} with h/d is presented in Fig. 3. The Nu_{avg} for the targeted surface without foam drops with the increase in the h/d due to a drop in the jet momentum. However, the effect of the h/d on Nu_{avg} is not witnessed for the targeted surface with attached and detached foam.

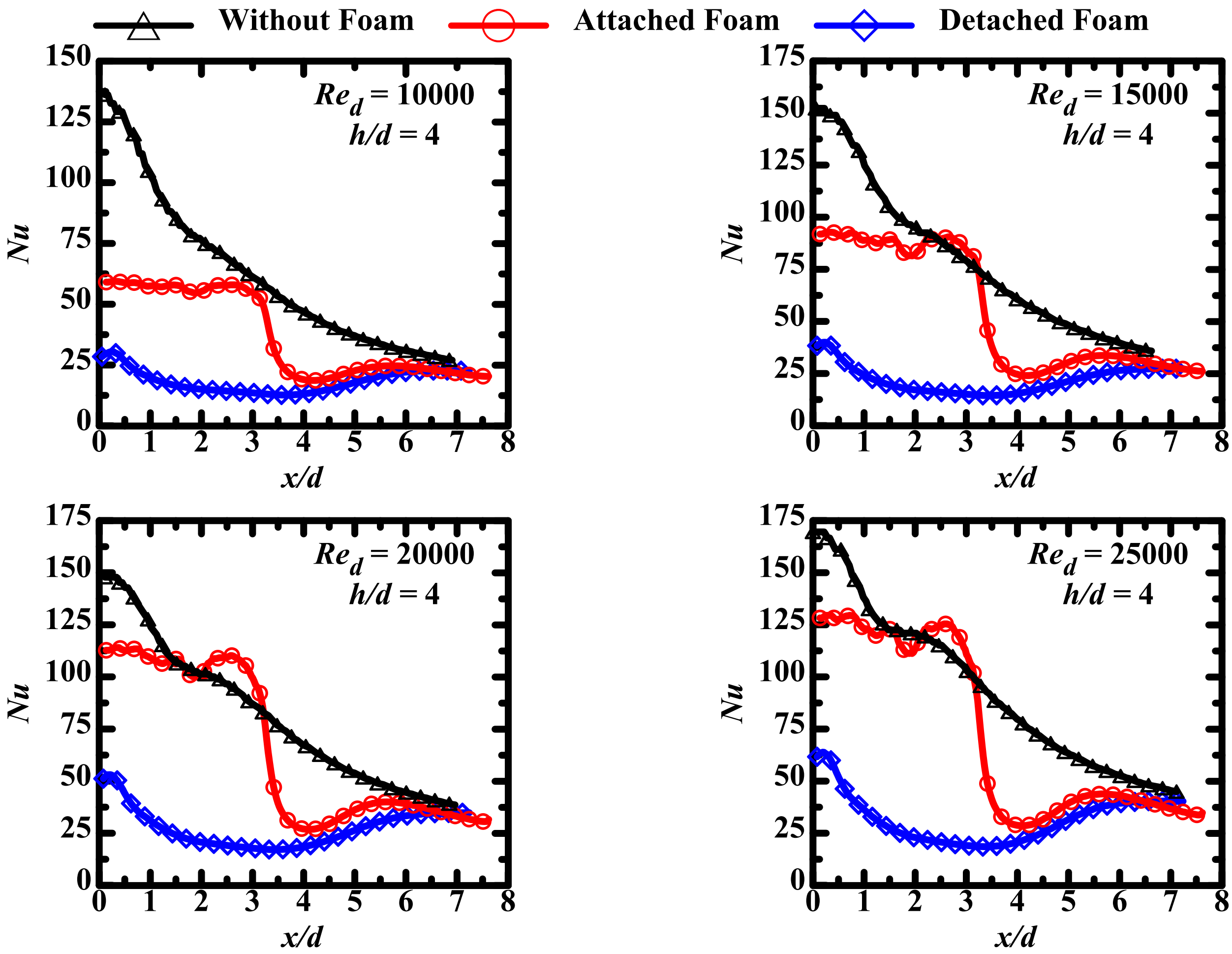

Fig. 2: Variation of coefficient of variance (*COV*) with *h/d*

The Nu_{avg} of the targeted surface with attached and detached porous foam is constantly lower than the targeted surface without foam at all the *h/d*s. Hence, the presence of the foam dampens the overall heat transfer from the targeted surface under jet impingement. However, as discussed in Fig. 2, the presence of the foam on a targeted surface offers uniform heat transfer. Hence, for the present case, the coefficient of the variance is computed using Nu_{local}. The coefficient of the ratio of the standard deviation of Nu_{local} to the corresponding Nu_{avg}. Mathematically, the coefficient of variance is given by Eqs. (4).

$$COV = \frac{\sigma_{Nu}}{Nu_{avg}} \times 100 \tag{4}$$

The lower *COV* value implies a more uniform heat transfer. For the present case, the coefficient of variance (*COV*) of the Nusselt number distribution is calculated for the area corresponding to *x/d* of ± 3.0 to *y/d* ± 2.5. Figure 3 shows the variation of the *COV* with *h/d* for different Reynolds numbers. The coefficient of the variance of the targeted surface without foam is independent of the *h/d* for the lowest Reynolds number of 10000. However, with an increase in the Reynolds number, the effect of the *h/d* on *COV* is witnessed. Similar to the targeted surface without foam, the *COV* for the targeted surface with detached foam also drops with the increase in the *h/d*. However, there is no effect of *h/d* is witnessed for the targeted surface with attached foam.

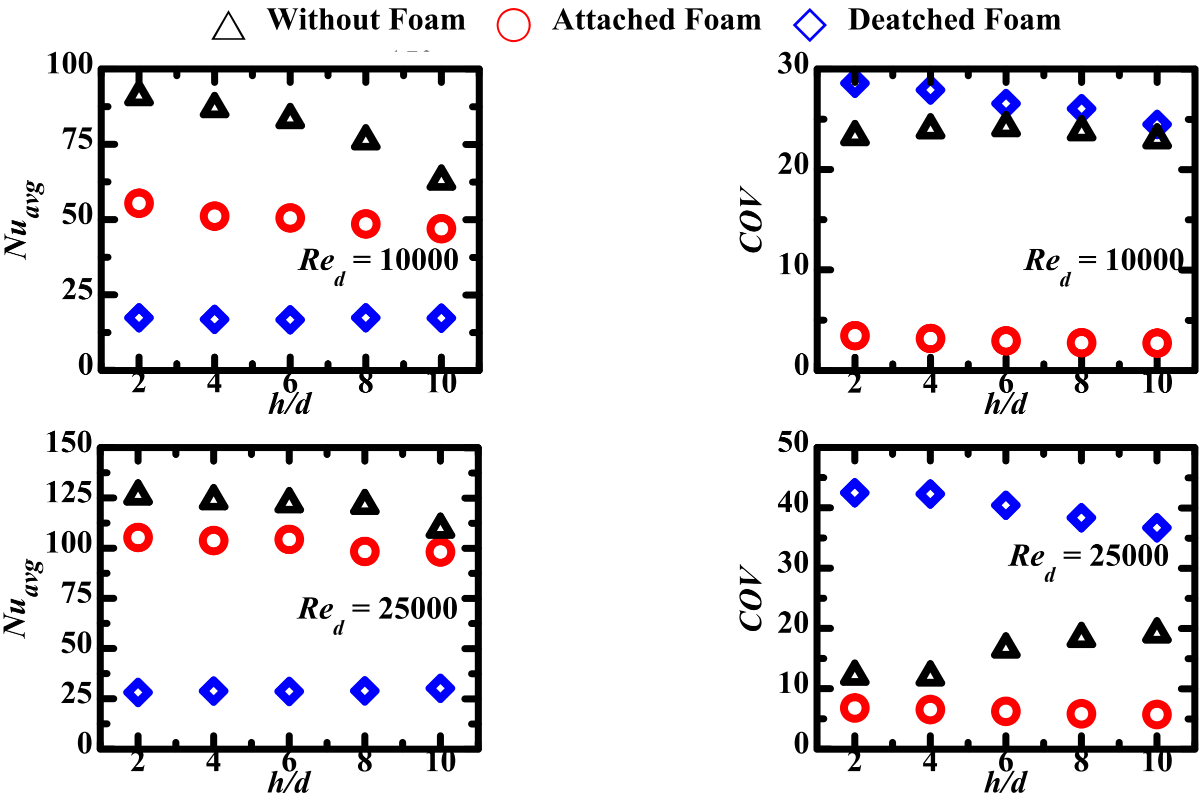

Fig.3: Variation of the (a) average Nusselt number and (b) coefficient of variance with *h/d*

For a given *h/d*, the *COV* for a targeted surface without foam decreases with the increase in the Reynolds number. Hence, the heat transfer is more uniform at a higher Reynolds number for a targeted surface without foam. This may be because the jet experiences a spread in the radial direction due to the entrainment of the surrounding air. Similar to the targeted surface without foam, the *COV* of the targeted surface with detached foam increases with the increase in the Reynolds number. This suggests that the heat transfer from the targeted surface with detached foam becomes nonuniform with the increase in the Reynolds number. The *COV* of the targeted surface with detached foam shows higher *COV* in comparison with the targeted surface without foam. However, the *COV* of the targeted surface with attached foam is consistently lower than the targeted surface without foam and with detached foam. Hence, pasting porous foam on the targeted surface makes the transfer of heat more uniform sur to the conduction heat transfer offered by the foam.

4. Conclusion

A targeted surface with and without porous carbon foam under single circular air jet impingement is investigated experimentally for local heat transfer. The 85 % porous carbon foam having 8 mm height is used for targeted surfaces with attached and detached conditions. Thin metal foil and IR imaging techniques are used for the measurement. The effect of the Reynolds number (Re_d = 10000, 15000, 20000 and 25000) and different distances between targeted surfaces and nozzle exit (*h/d* = 2, 4, 6, 8 and 10) is investigated. The coefficient of variance (*COV*) is calculated from the Nu_{local} measurement in order to investigate the uniformity of the heat transfer. The major findings from the study are listed below.

- The presence of the attached porous carbon foam on a targeted surface drops the heat transfer at all the locations in comparison with the targeted surface without foam independent of the Reynolds number.
- The average Nusselt number of the targeted surface with attached and detached foam is consistently lower than the targeted surface without foam.

- The transfer of heat from the targeted surface with attached carbon foam makes the heat transfer more uniform in comparison with the targeted surface without foam.
- The uniformity in the heat transfer for a targeted surface without foam increases with the increase in the Reynolds number and *h/d*. However, the uniformity in the heat transfer in the case of the targeted surface with the foam is independent of the Reynolds number and *h/d*.
- The comparison of the attached and detached foam targeted surface suggests that the presence of foam deteriorates the convection heat transfer offered by the jet. However, the foam also offers conduction heat transfer when the foam is attached to the targeted surface.
- The average and stagnation Nusselt number as well as the uniformity in the heat transfer (*COV*) drops with an increase in the different distance between targeted surfaces and nozzle exit

Acknowledgments

Authors acknowledge the efforts put in by Mr. Rahul Shirsat in building the experimental setup and fixing the mechanical problems during the experiments.

References

[1] H. Martin, “Heat and mass transfer between impinging gas jets and solid surface”, *Adv. Heat Transfer*, vol. 13, pp.PP. 1-60, 1977.

[2] W. H. Shih, F. C. Chou, W. H. Hsieh, “Experimental investigation of the heat transfer characteristics of aluminium foam heat sink with restricted flow outlet”, *ASME, J. of Heat Transfer*, vol. 129, pp. 1554 –1563, 2007.

[3] C. Y. Zhao, “Review on thermal transport in high porosity cellular metal foams with open cells”, *Int. J. Heat Mass Transfer*, vol. 55, pp. 13-14, 2012.

[4] J. J. Kuang, X. L. Wang, T. J. Lu and T. Kim, “Role of laminar length of round jet impinging on metal foams”, *J. of Thermophysics and Heat Transfer*, vol. 30, no.1, pp. 1- 8, 2016.

[5] W. H. Shih, C. C. Liu and W. H. Hsieh, “Heat-transfer characteristics of aluminum-foam heat sinks with a solid aluminum core”, *Int. J. of Heat and Mass Transfer*, vol. 97, pp. 742–750, 2016.

[6] W. H. Hsieh, J. Y. Wu, W. H. Shih and W. C. Chiu, “Experimental investigation of heat transfer characteristics of aluminium foam heat sinks”, *Int. J. Heat Mass Transfer*, vol. 47, pp. 5149–5157, 2004.

[7] W. H. Shih, W. C. Chiu and W. H. Hsieh, “Height effect on heat transfer characteristics of aluminium foam heat sinks”, *ASME J. Heat Transfer*, vol. 128, pp. 530–537, 2006.

[8] S. S. Feng, J. J. Kuang, T. Wen, T. J. Lu and K. Ichimiya, “An experimental and numerical study of finned metal foam heat sinks under impinging air jet cooling”, *Int. J. of Heat Mass Transfer*, vol. 77, pp.1063–1074, 2014.

[9] C. Byon, “Heat transfer characteristics of aluminum foam heat sinks subject to an impinging jet under fixed pumping power”, *Int. J. Heat Mass Transfer*, vol. 84, pp. 1056–1060, 2015.

[10] K. Yogi, K. Shankar and S. V. Prabhu, “Separation of conduction and convection heat transfer effects for a metal foamed flat plate impinge d by a circular jet”, *Int. J. of Heat and Mass Transfer*, vol. 185, pp. 122387, 2022.

[11] K. Yogi, M. Godase, M. Shetty, K. Shankar and S. V. Prabhu, “Experimental investigation on the local heat transfer with a circular jet impinging on a metal foamed flat plate”, *Int. J. of Heat and Mass Transfer*, vol. 162, pp. 120405, 2020.

[12] K. Yogi, K. Shankar and S. V. Prabhu, “Influence of metal foam thickness on the conduction and convective heat transfer for a flat plate with metal foam impinged by a rectangular slot jet”, *Int. J. of thermal sciences*, vol. 179, pp. 107665, 2022.

[13] R. J. Moffat, “Using uncertainty analysis in the planning of an experiment, ASME Journal Fluids Engineering”, vol. 107, no. 2, pp.173–178, 1986.

[14] V. Katti, S. V. Prabhu, “Experimental study and theoretical analysis of local heat transfer distribution between the smooth flat surface and impinging air jet from a circular straight pipe nozzle”, *Int. J. of Heat Mass Transfer*, vol. 51, pp. 4480-4495, 2008.