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STUDY OF TRANSIENT HEAT TRANSFER OF A SOLID WITH PROTECTIVE FABRIC UNDER HOT AIR JET IMPINGEMENT

MA Islam, AA Rezwan, S Hossain and AKMN Islam

Dept. of Mechanical Engineering
Bangladesh University of Engineering & Technology
Dhaka, Bangladesh

ABSTRACT

The present study focuses on the performance of fire protective clothing under the flame blast condition. This investigation has been conducted using a hot air jet that is impinged normally on a base plate with/without protective fabric to mimic the flame blast condition. The air jet temperature is 125^{o}C and the jet velocity is 15 m/s and 19 m/s. The temperatures at various radial positions of the solid are measured by thermocouples and are used to calculate the surface heat flux transferred to the solid base plate. Subsequently, the local heat transfer coefficient and the local Nusselt Number for different radial positions of the base plate have been estimated, exhibited and analyzed for different longitudinal distances between jet and based plate with/without protective fabric. The experimental results show a significant decrease in heat transfer rate using the protective fabric.

Keywords: Transient Heat Transfer, Jet Impingement, Hot Air Jet, Fire Protective Fabric.

1. INTRODUCTION

The thermal performance of protective clothing has been a point of interest for several decades. The protection of firefighters and other employees working in many hazardous environments against high heat flux exposure is very crucial for their safe guard and for others' safety as well. So, the protective clothing is essential requirement in daily business for the staff of Fire Fighting Department, Policemen and Navy Military Staff and also for the workers in many chemical and bio-hazardous industries. Fire Resistive (FR) clothing has steadily improved over the years as new fabric materials and improved designs have reached the market. But their performance has not been studied in much detail for the safe keeping of their users yet. Many of these studies are based on fire services field experience.

Most of this work dates back in 1960s' and 1970s' [1] when computers were significantly less advanced. Torvi [2] provides a review of work done on heat and mass transfer models applicable to fabrics in the high heat flux range that a firefighter may experience. The Government Industry Research Committee on Fabric Flammability considered mainly flammable fabrics used by the ordinary consumer [3-4]. Morse et al. [5] studied heat transfer and burn injury risk from exposure to jet fuel fires. Only three protective clothing materials were examined for use in US Air Force flight fabrics. Also, some model properties were determined by fitting the model results to experimental data. Stoll et al. [6-8] used a combination of analytical and experimental techniques to measure the thermal response of single fabric layers over skin. They developed diagnostics to rate the protection offered by a fabric with known properties. Their work eventually led to the thermal protective performance test. Many recent studies for the permeable protective fabric system have been conducted using air jet impingement. Many of these studies formulated a numerical model for comparing the thermal performance under various conditions [9]. Bamford and Boydell [10] developed a finite-difference-based burn injury evaluation code and Torvi [2] developed a finite element code to simulate the test. Very recently, Anguiano [11] performed an important study by using skin stimulant material to understand the extent of fire burn injury.

In the present study, jet impingement heat transfer has been experimented to simulate the flame impact to a solid surface covered with a FR fabric. Jet impingement has many practical applications due to its high heat and mass transfer. There are many factors affecting the heat transfer of jet impingement. These include the nozzle diameter (d), nozzle-to-plate distance (l), nozzle-exit velocity (v_{jet}), thermophysical properties of the jet fluids. These factors are normally lumped into dimensionless groups: Nu, Re, Pr and l/d, which are then correlated.

2. EXPERIMENTAL SETUP

The experimental study has been carried out by using a circular air jet facility as shown in Fig. 1. Detail explanation of different segment of the facility has been given in the previous studies [12-13]. The overall length of the flow facility is 9.0 m. It has axial flow fan unit, two settling chambers, two diffusers, a silencer and a flow nozzle. The fan unit consists of three Woods Aerofoil fans of the same series. The fan unit receives air through the butterfly valve and discharges it into the silencer of the flow duct. Flow from the silencer passes on to the settling chamber through a diffuser. At the discharge, side of this chamber there is a flow straighter and wire screen of 12 meshes to straighten the flow and to breakdown large eddies present in the air stream. Air from this chamber then flows to the second settling chamber through a nozzle and second diffuser. The flow straighter and wire screens are used here to ensure a uniform axial flow free of large eddies which may be present in the upstream side of the flow. The flow from the second settling chamber then enters the 100 mm long and 80 mm diameter circular nozzle. At the farthest end the diameter of the flow facility is reduced from 475 mm to 88.9 mm where the heating section is placed [12-13].

For producing hot air jet, an attachment shown in Fig. 2 has been installed. It includes a heating section of length 0.9 m consisting of 4 cartridge heaters of total power consumption of 3 kW. Five half circular baffles are placed in series in the heating section to enhance the heating capacity of the air. Air from the wind tunnel is passed through the entrance section, heating section and settling chamber, the finally through the nozzle to produce desired air jet.

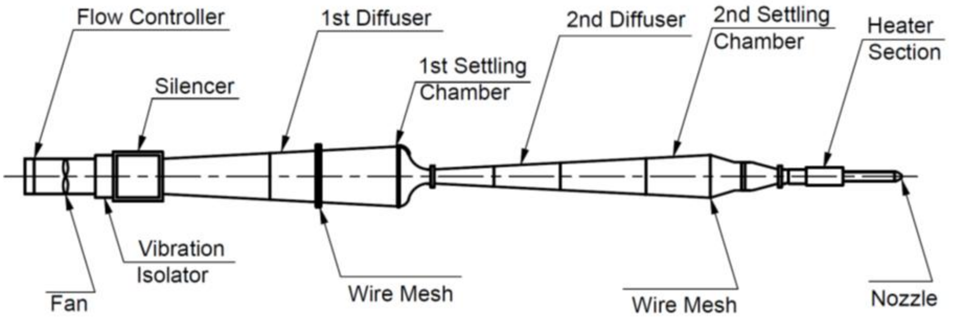

Fig 1. Wind Tunnel for the Circular Jet Facility [12**]**

Swirling effect of the air due to the baffles ensures the uniform heating air from the heater surface. The heated air then passes through the long settling chamber to the nozzle having a diameter of 25.4 mm. This is to note that the settling chamber is insulated with asbestos cloth and heat tape to prevent the heat loss to the surrounding from the hot air.

The air flow through the nozzle is controlled by regulating the speed of the fan units. The temperature of the jet is regulated by controlling the supply voltage of the heater. The whole setup is mounted on rigid frames of M.S. pipes and plates and these frames are securely fixed with the ground so that any possible unwanted vibration of the system is reduced to a minimum. To avoid the effect of ground shear, the setup is installed at an elevation of 1.4 m from the ground.

For the present investigation, a nozzle diameter of 25.4 mm is used. The temperature of the jet impingement has kept within 125°C. The test has been performed for two jet velocity, 19 m/s and 15 m/s. For protective clothing, an Aluminized glass fiber with vapor absorbent stitched with Kevlar fiber has been used. The base plate is made of Masonite, which is used for making hard board. Seven K-Type (Ni-Cr/Ni-Al) thermocouple is installed in the base plate to measure the temperature.

One thermocouple is placed at the stagnation point, and 3 others in both top and bottom side from the centered thermocouple are placed on the Masonite plate (base plate) at a distance of 1.5 nozzle diameter from each. A wooden frame is used to hold the fabric and the base plate as per provisions outline in ASTM code [14] . The wooden frame can be displaced along longitudinal axis with the wind tunnel for different l/d locations from the nozzle. The data has been recorded using a data acquisition system (Picosoft).

Table 1: Experimental Conditions

Parameters	**Values**
Jet Velocity (m/s)	19, 15
Temperature (°C)	125
Nozzle Dia (mm)	25.4
l/d	2, 4, 6
r/d	-4.5 ~ 4.5

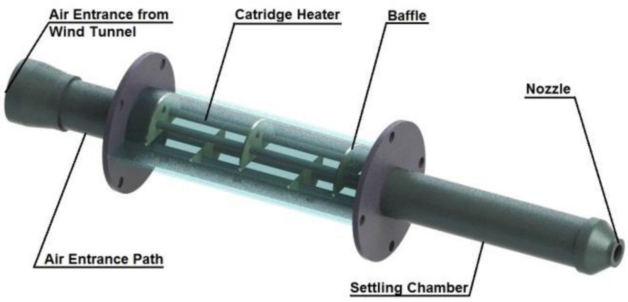

Fig. 2: Heater Section in Detail

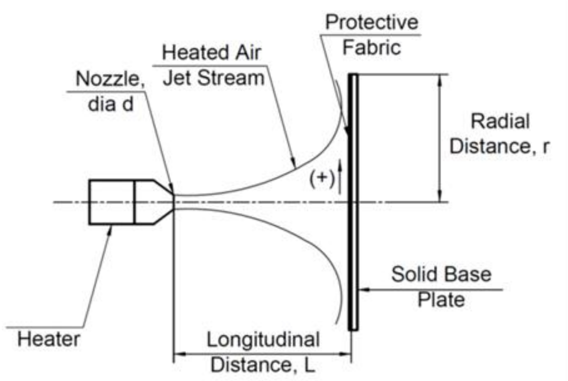

Fig. 3: Coordinate of the Setup

3.1 Experimental Procedure

The fan motors of the tunnel were first started for a particular air flow with the help of butterfly valve and run for about 15 minutes isolating the base plate by an isolator made of MS plate with circulating water. The power to the heating section has been supplied for the desired air temperature keeping the base plate isolated and waited unlit the desired steady temperature of the air jet has been reached. At the same time picosoft system was made ready for data recording. Then the hot air jet was impinged on the base plate by removing the isolator and the thermo couple readings were recorded for about three minutes. The same experiments were repeated for different conditions as given in Table -1. The collected data were used to estimated surface heat flux, heat transfer co-efficient and Nusselt numbers following the mathematical protocols given in Section 3.2 with a view to getting heat transfer performance of the base plate under jet impingement.

3.2 Mathematical Formulation

The base plate under jet impingement can be modeled as semi-infinite solid having a boundary of constant heat flux. Considering this, one can easily find the temperature distribution within the base plate as given in Eq. (1) [15-16].

$$T(x,t) - T_i = \frac{2q\sqrt{\alpha t/\pi}}{k} e^{\left(\frac{-x^2}{4\alpha t}\right)} - \frac{qx}{k}\left(1 - \operatorname{erf}\left(\frac{x}{2\sqrt{\alpha t}}\right)\right) \quad (1)$$

On the surface (x=0) this equation reduces Eq. (2) where T(t) are record during experiments and can be used to calculate the surface heat flux.

$$T(t) - T_i = \frac{2q\sqrt{\alpha t/\pi}}{k} \quad (2)$$

Given a heat flux at a particular location and time, Newton's law of cooling can be used to calculate the local heat transfer coefficient, h using Eq. (3).

$$q = h(T_{jet} - T_i) \quad (3)$$

The local Nusselt number as defined by Eq. (4) at any radial location, r/d, was derived from the surface heat flux history.

$$Nu = \frac{hd}{k} \quad (4)$$

Table 2: Thermal Properties of Masonite (Base plate)

Properties	Value
k	0.18 W/m.°C
ρ	1050 kg/m^3
C_p	1.34 kJ/kg.°C

4. RESULTS AND DISCUSSIONS

A total of 12 experiments were performed yielding over 16,000 data points for different conditions as given in Table 1. The surface heat flux and Nusselt number variation for different experimental conditions are displayed and analyzed in this section.

Figure 4 shows the variation of surface heat flux at the stagnation point of the base plate with and without fire resistant (FR)/protective fabric. In this figure, the red (upper) curve represents the condition for base plate without FR fabric and the blue (lower) curve represents the condition with FR fabric attached to the plate. As shown in the figure, the heat flux of the base plate without the FR fabric rapidly increases and then slowly decreases with the increasing time. The maximum heat flux is 3.7 kW/m^2 and occurs within 10 second from the commencement of the jet impingement. The heat flux of the base plate with the FR fabric follows a different trend as shown. The heat flux in this case increases suddenly at the beginning and then decreases slowly having the values much lower than those without fabric.

Figure 5 exhibits the variation the Nusselt number past the stagnation point of the base plate at l/d = 2 after 30s of jet impingement. Here, the red line represents the case without the FR fabric and the blue line represents the condition with FR fabric. As shown in the figure it is clear that the local Nusselt number (local heat transfer coefficient as well) with FR fabric is much lower than that of without FR fabric. For the case without FR fabric, the Nusselt number at the stagnation point is much higher, while for the case with FR fabric it is much lower and more uniform.

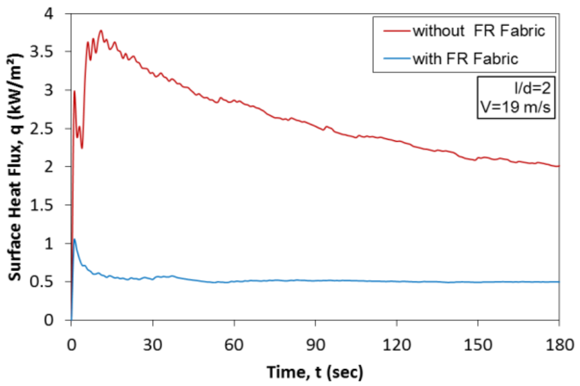

Fig 4. Surface Heat flux variation with time

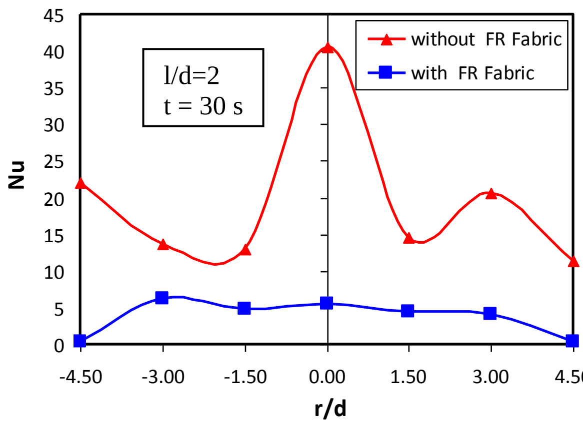

Fig 5. Radial Nusselt number distribution

4.1 Transient Effects on Nu

Figure 6 and 7 shows the Nusselt number distribution for later intervals. At interval time t=65s the Nusselt number is slightly increased from the previous interval for both cases. This is the maximum heat transfer coefficient. After this time interval the heat transfer converges to steady state and the heat transfer coefficient decreases. This is also the assumption for the semi-infinite solid theory. The distributions of Nusselt number for various radial directions are much more uniform then the previous time interval. For a further later interval of t=180s, the heat transfer coefficient decreases more than the previous time interval.

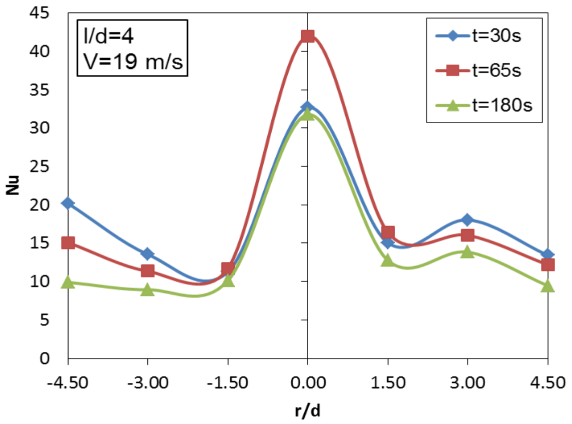

Fig 6. Effect of Exposure Time without FR Fabric

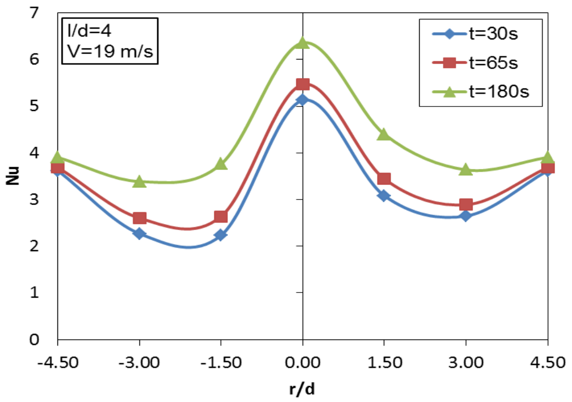

Fig 7. Effect of Exposure Time with FR Fabric

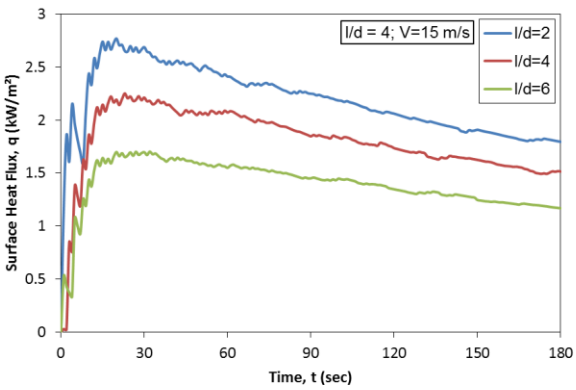

Fig 8. Effect of l/d on surface heat flux without FR fabric

4.2 Effect of Space Between Plate and Nozzle (l/d)

Figure 8 shows the surface heat flux of the base plate for different nozzle to plate separations. For the base plate only the heat flux to time curve follow a similar trend for the entire nozzle to plate separation. For lower nozzle to plate separation the heat flux is higher and decreases with increasing distance.

Figure 9 shows the surface heat flux of the base plate with the FR fabric. For l/d of 4 and 6, the curve follows a similar trend. But for l/d of 2 the curve follows a different trend. It suddenly increases with the start of impingement and then decreases to the steady state.

The radial local Nusselt number distribution for larger nozzle to plate separation (Figs. 10 and 11) depicts a much more complete distribution, with a pick at the stagnation point and decreases with the increasing radial position. But for l/d of 2 with FR fabric, the result shows a deviation from other two l/d separation. Here a secondary pick has been seen with the pick at stagnation point.

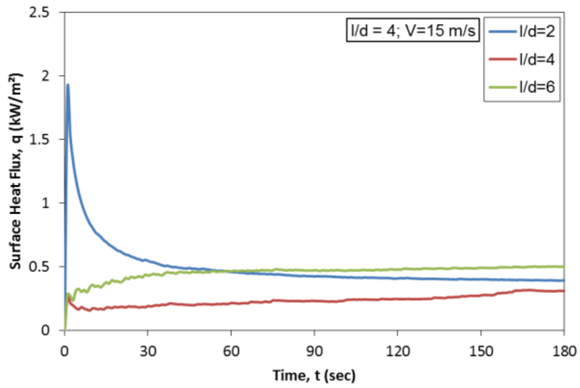

Fig 9. Effect of l/d on surface heat flux with FR fabric

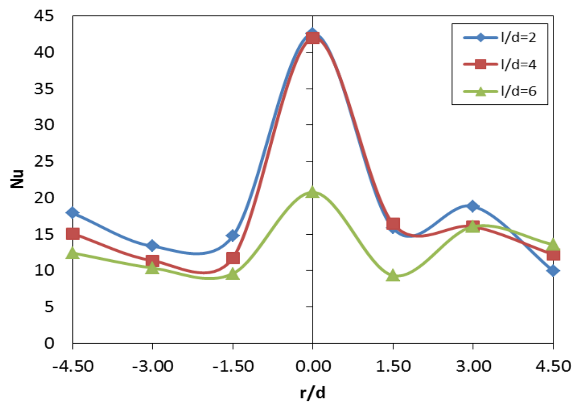

Fig 10. Effect of l/d on Nu without FR fabric at t=65 s

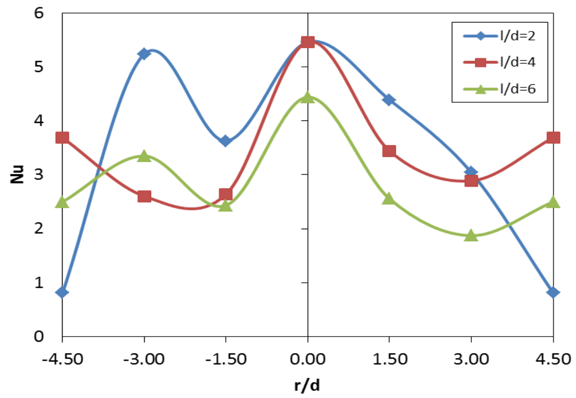

Fig 11. Effect of l/d on Nu with FR fabric at t=65 s

4.3 Effect of Velocity on Surface Heat Flux

The lower velocity of the impinging jet depicts a lower maximum heat flux for stagnation point and subsequent radial position than the higher velocity. But like the higher velocity air jet impingement, similar trends for the heat flux are observed for lower velocity.

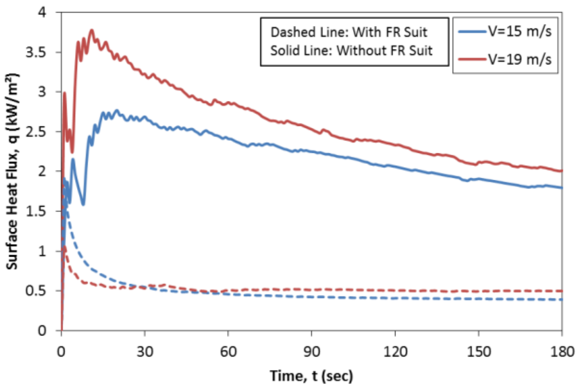

Fig 11. Effect of Velocity on Heat Flux for l/d = 2

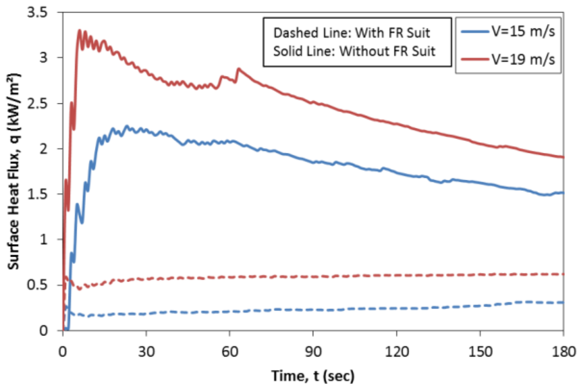

Fig 12. Effect of Velocity on Heat Flux for l/d = 4

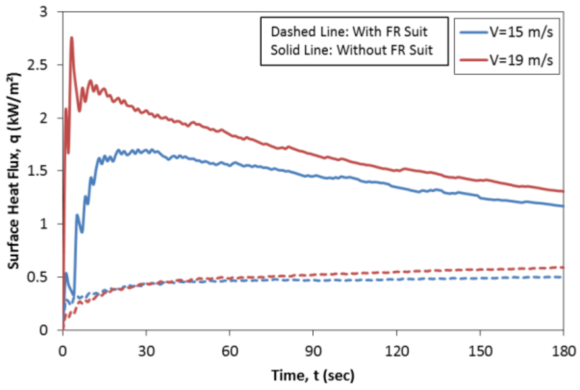

Fig 13. Effect of Velocity on Heat Flux for l/d = 6

In Figs. 11-13, the effects of velocity on surface heat flux have been shown. The surface heat flux of the base plate for velocity 19 m/s has been found higher than for 15 m/s with/without FR fabric. But with the FR fabric, the heat flux for velocity 15 m/s increase to a higher value suddenly after the start of jet impingement than for velocity 19 m/s for the position of l/d = 2 only. For other l/d position the heat flux for the earlier case has been found to be higher than the latter case.

5. CONCLUSION

Experiments are conducted using a hot air jet impinged on a base plate with/without protective fabric to mimic the flame blast condition for different experimental conditions. The temperatures measured are used to calculate the surface heat flux transferred to the solid base plate. Moreover, the local heat transfer coefficient and the local Nusselt Number for different radial positions of the base plate have been exhibited and analyzed in this study. The results show a significant decrease in heat transfer rate using the protective fabric. The setup can be used for testing the heat transfer capability for any kind of fabric layer used for different purposes.

7. ACKNOWLEDGEMENT

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8. REFERENCES

1. Chen, N.Y., 1959, “Transient Heat and Moisture Transfer Through Thermally Irradiated Cloth.” Ph.D Thesis, Massachusetts Institute of Technology, Cambridge, Mass., USA.
2. Torvi, D. A., 1997, “Heat Transfer in Thin Fibrous Materials Under High Heat Flux Conditions”, Ph.D Thesis, University of Alberta, Calgary, Alberta.
3. Backer, S., Et al., 1976, *Textile Fabric Flammability*, The MIT Press, Cabridge, Mass., USA.
4. Wulff, W., Zuber, N., et al., 1972, “Study of Hazards from Burning Apparel and the Relation of Hazards to Test Methods,” Second Final Report: Georgia Institute of Technology, NTIS: COM-73-10956
5. Morse, H.L., Green, K. A., Thompson, J. G., Moyer, C. B., and Clark, K. J., 1972, “Analysis of the Thermal Response of Protective Fabrics,” Technical Report, Acurex Corp., Mountain View, Calif., USA
6. Stoll, A. M., Chianta, M. A., and Munroe, L. R., 1964, “Flame-Contact Studies,” Transactions of the ASME, Journal of Heat Transfer, Vol. 86, pp 449-456
7. Stoll, A. M. and Chianta, M. A., 1968, “Burn Protection and Prevention in Convective and Radiant Heat Transfer.” Aerospace Medicine, Vol. 39, pp. 1097-1100
8. Stoll, A.M. and Chianta, M.A. “Method and Rating System for Evaluation of Thermal Protection,” Aerospace Medicine, Vol. 40, No. 11, pp. 1232-1238
9. Lee, S., Park, C., Kulkarni, D., Tamanna, S., Knox, T., 2010, “Heat and Mass Transfer in a Permeable Fabric System under Hot Air Jet Impingement”, Proc. Int. Heat Transfer Conf. (IHTC14).
10. Bamford, G. J. and Boydell, W., 1995, “ICARUS: A Code for Burn Injury Evaluation”, Fire Technology, Vol. 31, No. 4, pp. 307-335
11. Anguiano, R. M., 2006, “Transient Heat Transfer through Thin Fibrous Layer”, M.Sc. Thesis, University of Alberta, Emonton, Albarta, Canada.
12. Ali, M. A. T., Bhattacharjee, S., 2009, “Experimental Study of Thermally Stratified Co-Axial Jets with Trip Ring Excitation”, *Proc. Int. Conf. on Mechanical Engineering (ICME2009).*
13. Hasan, M. N., 2008, “Experimental Study of Flow Characteristics in the Near Field of a Thermally Stratified Co-axial Free Jet”, M.Sc. Thesis, Bangladesh University of Engineering & Technology, Dhaka, Bangladesh.

14. ASTM F2703-08, “Standard Test Method for Unsteady-State Heat Transfer Evaluation of Flame Resistant Materials for Clothing with Burn Injury Prediction”
15. Mills, A. F., *Basic Heat and Mass Transfer*, 1995, Richard D Erwin, Inc., Chicago, USA.
16. Holman, J. P., 2008, *Heat Transfer*, Tata McGraw-Hill, New Delhi, India.

9. NOMENCLATURE

Symbol	**Meaning**	**Unit**
T	Temperature	(°C)
q	Heat Flux	(W/m)
α	Thermal Diffusivity	(m^2/s)
k	Thermal Conductivity	(W/m.°C)
ρ	Density	(kg/m^3)
C_p	Heat Capacity	(kJ/kg.°C)
h	Heat Transfer Coefficient	(W/m.°C)
v	Velocity	(m/s)
Re	Reynolds Number	-
Nu	Nusselt Numeber	-
t	Time	(s)
l	Nozzle to Plate Distance	(mm)
d	Nozzle Diameter	(mm)
r	Radial Distance	(mm)

Superscripts and Subscripts	
x	Axial Position
n	Interval Number
i	Surface
jet	Impinging Jet
avg	Average
Abbreviation	
FR	Fire Resistive

10. MAILING ADDRESS

Dr. Md. Ashraful Islam
Professor
Department of Mechanical Engineering
BUET, Dhaka-1000, BANGLADESH.
Phone : 88029665650-80 (Extn. 7980(O)), 8801914220502 (M).
FAX : 880-2-8613046
E-mail : aislam@me.buet.ac.bd