Effect of air jet velocity and angle on the performance of air curtain at different pressure difference conditions

AMITESH PAUL, A.C. TIWARI
University Institute of Technology, Rajiv Gandhi Proudyogiki Vishwavidyalaya, Bhopal, India

Abstract

Air curtain door system or air door system is a mechanism or method used to separate two different environmental conditions or two different atmospheres and contaminants existing from one space to another with the help of blower fan mounted toward downwards at the entrance of building with respect to the door height. While flow of air across the door are basically characterized in to two categories that is intrinsic and extrinsic flow of air. Here in this work, parametric evaluation of different parameters of air curtain were performed. In this work different air curtain performance were analyzed numerically. For performing the numerical analysis of air curtain, here in this work Ansys (Fluent) was used. To analyze the effect of different pressure difference across the door, in this work fourteen pressure difference condition across the door were analyzed numerically. For analyzing effect of difference velocity of air jet on air curtain performance, this study considered 5, 7, 9, 11, 13 and 15 m/s velocities of air jet and calculates volume flow rate of air at outer outlet. With 15 m/s velocity of air jet, the air curtain is able to restrict the flow of air up to 20 Pa pressure difference across the door. The effect of different air jet angle on the performance of air curtain was also analyzed with the help of CFD analysis. For calculating the effect of different air jet angle on volume flow rate of air at outer outlet, in this work it considered six different inclination angle of air curtain jet that is 0, 5, 10, 15, 20 and 25 degree. Through analysis it is found that, for each pressure difference 15 degree inclination angle of air curtain jet shows the minimum volume flow rate of air.

Keywords- air curtain, jet angle, jet velocity, pressure difference, volume flow rate

1. Introduction

Air curtain or air door is a device to prevent two different atmospheres and contaminants existing from one space to another with the help of blower fan mounted downwards to the entrance of building with respect to the door height. Air infiltration is the hysterical outflow of outside air to buildings over the slots in the building envelope or with the help of large overtures such as doors (ASHRAE, 2009). The loss of air, the crusade of air inside or outside the buildings, is primarily due to the difference in pressure between the various elements of the building enclosure [7]. Pressure differences can initiated by many aspects, such as chimney influence, wind and / or imbalances in the HVAC system (ASHRAE, 2010). The construction sector (residential, institutional and commercial buildings) consumes around 41% of primary energy consumption. In general, for different types of commercial buildings, estimates rise to 18% analysed by L. Leon Wang, Z. Zhong, 2014 [9]. As building materials and construction methods develop, modern buildings are built with greater strength and are better insulated. In more recent buildings (modern and well insulated), most of the heat losses contribute to air infiltration. Viegas et.al [2018] this research project proposed an air curtain designed to guarantee an adequate separation between two areas, one clean and one contaminated. Vertical air curtains have often been used to disperse two different climate zones in order to reduce heat transfer. Linden et.al [2016] through this paper, they had investigated the properties of a differing buoyancy force on the concert of an air curtain in the entrance which separates a warm indoor atmosphere from the cold exterior. Gao et.al [2016] their investigation was done for Subway tunnel fires habitually upshot in catastrophes and heavy casualties. OTES air systems have mounted to aid people for evacuate from fire. Dan et.al [2015] In this work, a dynamic grid technique was used to investigate the law of propagation of smoke flow in the tunnel when the floor of a subway train burned and to compare the effect of the modes of longitudinal ventilation of smoke movement when the burning train stops. Frank et.al [2014] in this study, they had researched the effectiveness of an air curtain in the threshold of a aired building by employing equally hypothetically and experimentally. Kardekar et.al [2013] In this work, a study was conducted to established a relationship between the power absorbed by the air curtain and the performance of the air curtain in terms of the rate of exhaust air from it.

Cowlard et.al [2013] the aimed of the following research was to highlight the essential elements of a high-rise fire safety strategy and to try to highlight some specific overall performance goals. Fu et.al [2013] this document originally provided an overview of the tools and methods included in the normal PTV programming for the indoor environment, and then introduced the corresponding PTV program to measure the flow of air inside. Gil-Lopez et.al [2013] the doors that are being surveyed are part of the refrigerator room that gets higher and energy loss. The main purpose of this study is to achieve more efficient energy management for these areas. Diaz-Ovalle et.al [2012] the curtains that are being investigated have been modelled here as they have demonstrated its effectiveness in reducing some of the toxic concentrations in thick clouds. Zhang et.al [2012] In this study, experiments were carried out to investigate the enhancement of the concentration of CO concentration and the smoke transfer process in the tunnel sampling of slopes of -10 ° to 10 °, compared to the horizontal and different sizes. Zhiqiang et.al [2012] in this work, the results suggest that the expansion of the drainage stream addresses the problems of the hospital's operating room and provides a low level of contamination.

To calculate the effect of change in air flow angle and different velocity of air coming from the air curtain on the performance of air curtain system, here in this present work a parametric evaluation of different air flow angle and different velocity of air is performed at different pressure difference. In order to evaluate the effect of different air flow angle, it considered six different air flow angles that are 0, 5, 10, 15, 20 and 25. The value of volume flow rate of air was calculated for all air flow angle at different pressure difference to measure the feasibility of different angle at different pressure difference. To analyze the effect of different velocity of air curtain jet here it considered six different velocity air jets that are 5, 7, 9, 11, 13 and 15 m/s. At different velocity of air jet it calculates the value of volume flow rate of air at different pressure difference across the door.

2. Development of solid model

For analyzing the different process parameter and achieve objectives of the work, here first it has to develop the CFD model of air curtain mounted at the top of the door. The geometrical parameters on which the solid model of numerical analysis was developed were considered same as considered during the experimental analysis performed by Goubran et.al [35]. Room length is 2.44 m, room width is 2.44 m, room height is 1.3 m and Nozzle shot 0.08 m. Here in this work it perform the 2D analysis of air curtain the solid model of air curtain considered for the numerical analysis were shown in the below fig.

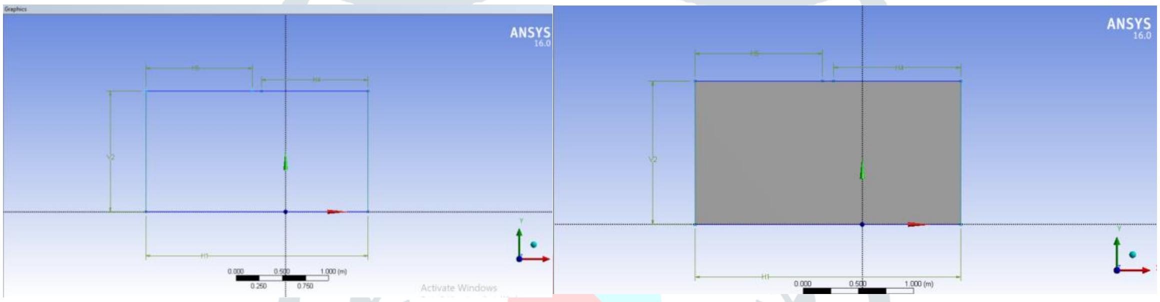

Figure 1: shows the geometric parameters considered for the numerical analysis

After developing the 2D model for numerical analysis, it is then perform mesh. Meshing of the solid model of air curtain were shown in the below section. For developing the initial model of air curtain for numerical analysis here it considered 20 degree inclination angle of air guiding fin, which means the guiding fins of air making an angle of 20 degree with the horizontal plane.

3. Meshing

In order to perform numerical analysis it is necessary to discretize the complete body in to number of nodes and elements. For performing the numerical analysis it is necessary to find the optimum number of nodes and elements to get good result and also perform the mesh independence test. Mesh independence test shows the dependency of numerical result on number of nodes and elements. In order to perform the independence test of numerical analysis here it considered five different numbers of nodes and elements to perform mesh and see the contours of velocity and jet length which is able to restrict the flow of air in both sides that is intrinsic and extrinsic. In order to get better contours of velocity and jet of air coming from curtain, more refinement is needed for meshing. In order to get the more refinement here we have considered refinement tool and give 8 mm size of element for meshing. The mesh with the given condition is shown in the below fig.

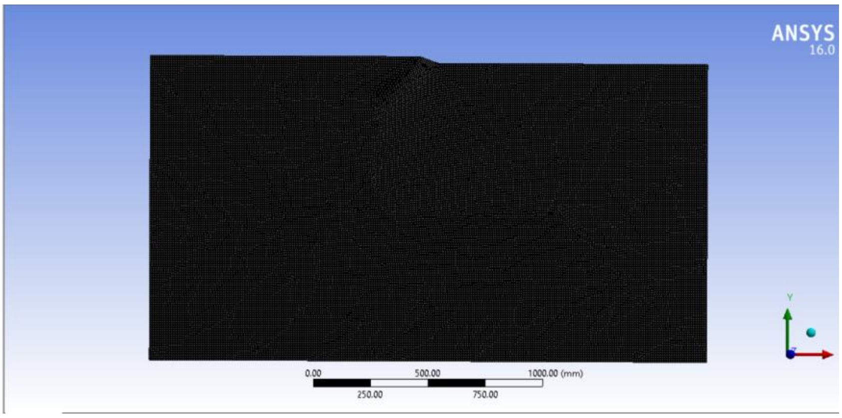

Figure 2: mesh of the geometry with 78958 numbers of elements

4. Selection of Model

For finding the optimum model for the numerical analysis of air curtain here in this work it perform the CFD analysis of air curtain with different model and find out the optimum model for the numerical analysis of air curtain. In order to find the optimum model here we have considered numerical analysis of air curtain based on the geometric conditions as mention in above section. With the same geometric parameters and boundary condition that is pressure different 2, 4, 6, 8 and 10 Pa at air velocity 9.1 m/s coming from air curtain it perform the numerical analysis and calculate the discharge (Q (m^3/s)) from the door. The comparison of discharge with respect to pressure difference for different models were shown in the below table.

Here in this work it first perform the CFD analysis of air curtain with different models that is K-epsilon Realizable, standard, RNG and K-omega standard and BSC model to find out the infiltration and exfiltration of air from door at different pressure difference. Through analysis it is found that the volume flow rate of air for K-epsilon Realizable model is in between the value of volume flow rate of air obtained with the different model used for the CFD analysis. Here in this work for further CFD analysis K-epsilon Realizable turbulence model is used as a turbulence model, and the pressure velocity coupling were adopted the SIMPLE algorithm. Here it also considered the standard wall function parameters with full buoyancy effect. During the CFD analysis of air curtain air was assumed as incompressible ideal gas. To get the more accurate result during the CFD analysis here convergence will reach when the residual was less than 10^{-3}. The comparison graph for different model used for the CFD analysis is shown in the below fig.

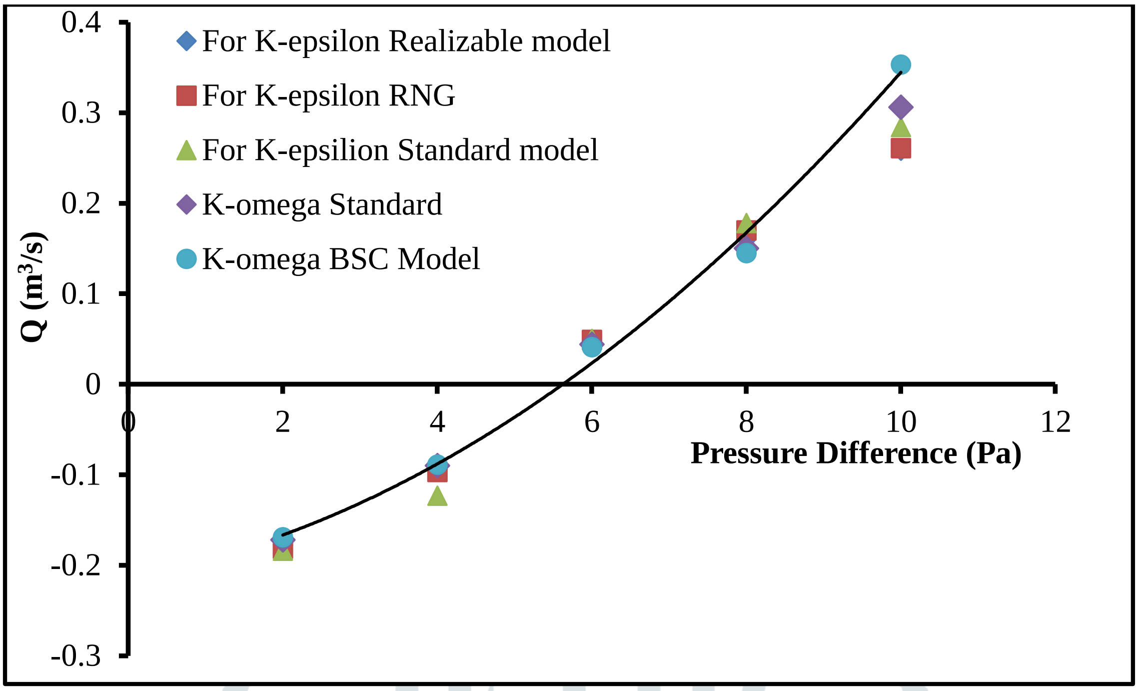

Figure 3: value of discharge for different models used for the CFD analysis

From the above graph it is found that there is slit variation in the volume flow rate of air for different model. To perform the numerical analysis here it considered the middle range of volume flow rate of air, which is obtained with the help of K-epsilon Realizable model.

5. Boundary Condition

During the analysis spatial discretization scheme were used for the analysis. For pressure interpolation, momentum and energy interpolation second order were chosen for the CFD analysis. Different numbers of elements and nodes were considered during the CFD analysis as mention in the above section. For the initial analysis of air curtain here it considered different pressure difference in between the inner and outer atmospheric condition. Air coming from the curtain at a velocity of 9.1 m/s and 13.75 m/s was considered for the initial analysis of air curtain. For validating the CFD model of air curtain velocity profile for different pressure difference that is 0.2, 3.6, 6.4, 7.3 and 8.7 Pa as considered during the experimental analysis performed by Goubran et.al [35] were find out through numerical analysis. Through numerical analysis it calculates the value of volume flow rate of air form door during intrinsic and extrinsic condition.

6. Validation of the CFD Analysis

Through CFD analysis here it calculates the value of volume flow rate of air through door at different atmospheric condition across the door. After calculating the value of flow rate of air and air curtain jet through numerical analysis it is then compared with the experimental analysis performed by Goubran et.al [35]. The comparison of value of volume flow rate of air is shown in the below fig.

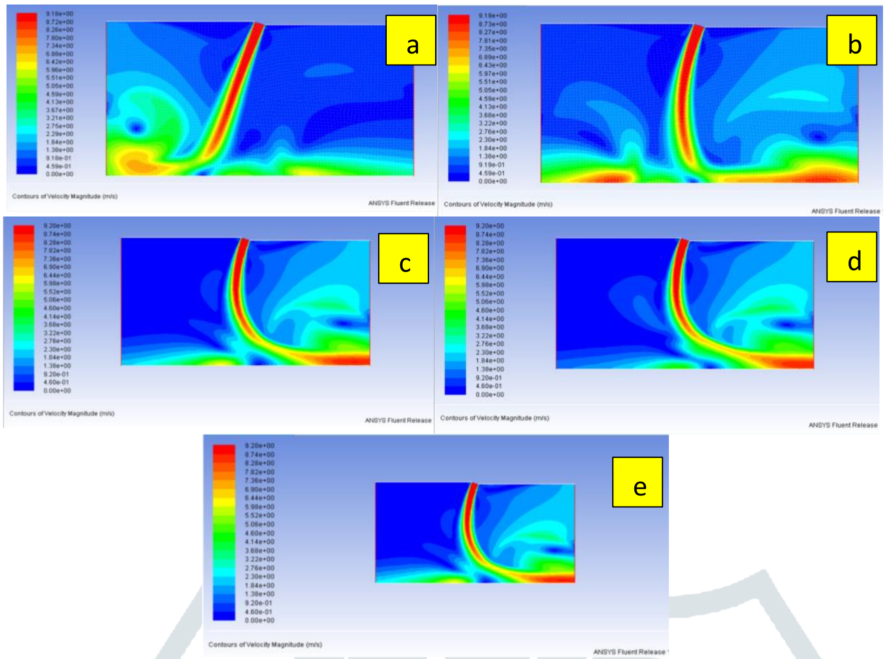

Figure 4: (a) Air curtain jet for 9.1 m/s velocity at 0.2 Pa pressure, (b) Air curtain jet for 9.1 m/s velocity at 3.6 Pa pressure, (c) Air curtain jet for 9.1 m/s velocity at 6.4 Pa pressure, (d) Air curtain jet for 9.1 m/s velocity at 7.3 Pa pressure, (e) Air curtain jet for 9.1 m/s velocity at 8.7 Pa pressure.

From the above analysis it is found that the air curtain jet at different pressure drop with 9.1 m/s velocity were same as analyzed during the experimental and numerical analysis performed by Goubran et.al [35]. Through analysis it is found that the air curtain jet with 9.1 m/s velocity is capable to restrict the intrinsic and extrinsic flow of air. Through analysis it is also found that there is some volume of air flow during the each pressure difference of door. From the above fig. following point is concluded (1) fig. (a) Shows the air curtain jet at 0.2 Pa pressure difference during this case the jet is able to restrict the intrinsic and extrinsic flow across the door. (2) Fig. (b) Also shows the restriction of both types of flow and able to reach the ground floor and trap different particles and air coming from the outside. (3) Whereas fig. (c), (d) and (e) show the jet of air curtain which is not able to restrict the flow of outside air which is called as intrinsic flow of air. Based on the above analysis it also validates the CFD model of air curtain having 13.75 m/s velocity air jet. In order to analyze the stability of air jet at different pressure difference here it considered different pressure difference that is 4.7, 10.3, 11, 13.4 and 17.1 Pa. The contours of air curtain jet at different pressure difference is shown in the below figures.

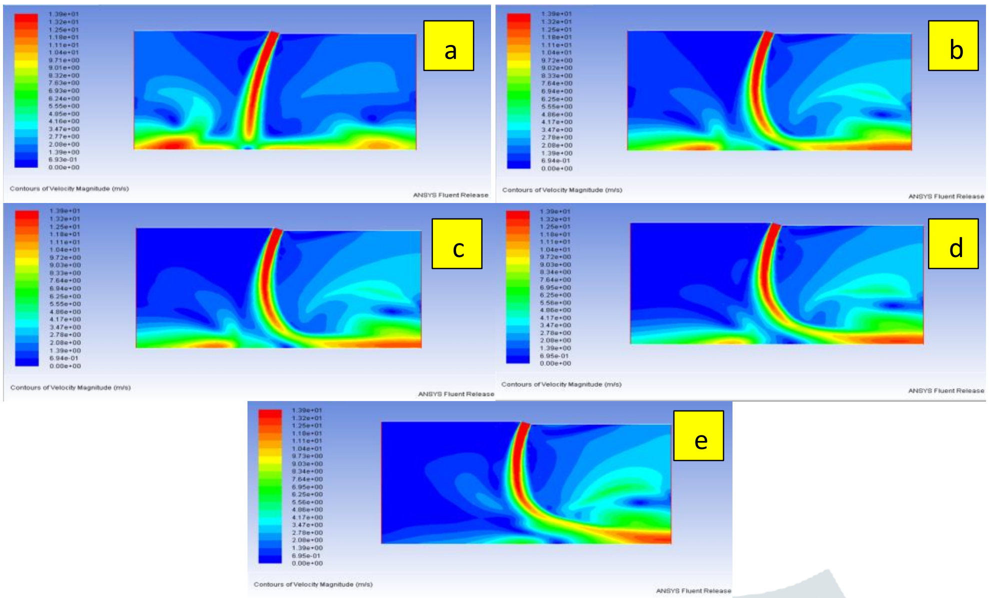

Figure 5: (a) air curtain jet for 13.75 m/s velocity at 4.7 Pa pressure, (b) air curtain jet for 13.75 m/s velocity at 10.3 Pa pressure, (c) air curtain jet for 13.75 m/s velocity at 11 Pa pressure, (d) air curtain jet for 13.75 m/s velocity at 13.4 Pa pressure, (e) air curtain jet for 13.75 m/s velocity at 13.4 Pa pressure.

From the above analysis it is found that as the velocity of air curtain increases the ability of air curtain jet to restrict the intrinsic flow of air at much higher pressure difference as compared to 9.1 m/s velocity of air. Fig. (a) Show the jet with 13.75 m/s velocity at 4.7 Pa pressure difference, in this case the jet of air is straight toward the floor and cannot allow the intrinsic flow of outer air. Where as in fig.(d) and (e) it is found that the air jet bend toward the inner side which allow the intrinsic flow of air that the outside air allow to move inside the system. The value of volume flow rate of air at different pressure different for 9.1 and 13.75 m/s velocity of air curtain is shown in the below fig.

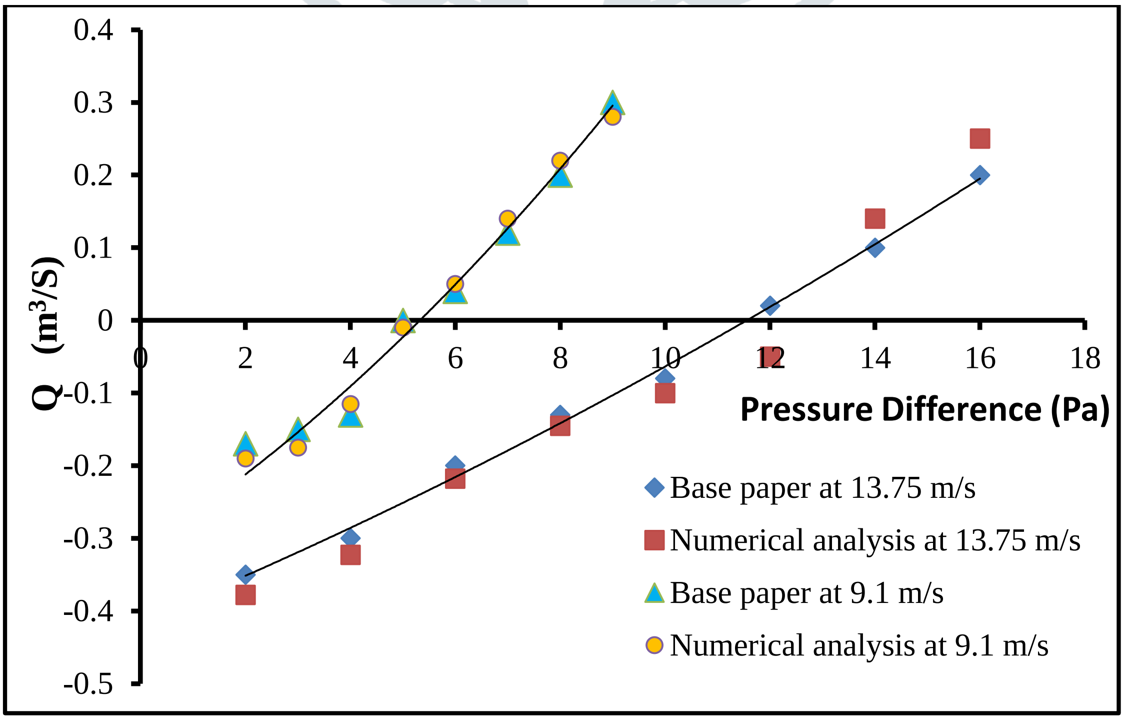

Figure 6: comparison of volume flow rate of air at different pressure difference with 9.1 and 13.75 m/s velocity of air curtain jet

From the above graph it is found that the value of volume flow rate of air at different pressure with different velocity of air curtain jet obtained through the CFD analysis is near to the value of volume flow rate of air obtained from experimental analysis performed by Goubran et.al [35]. Through analysis it is found that with positive pressure difference that is outside pressure is higher as compared to inside, volume flow rate of air for 9.1 m/s velocity remain negative for pressure up to 5 Pa which shows the restriction of outside air flow toward inside. After reaching the pressure difference 6 Pa the jet of air bend toward the inside and allow outside air to flow inside. Through graph it concludes that the value of volume flow rate of air calculated through numerical analysis is near to the value obtained from the experiment at every pressure difference and at every velocity of air curtain jet.

7. Effect of different air supply angle

To calculate the effect of change in air flow angle and velocity of air coming from the atmosphere on the performance of air curtain, here in this present work a parametric evaluation of different air flow angle and different velocity of air is performed. In order to evaluate the effect of different air flow angle, here it considered six different air flow angles that are 0, 5, 10, 15, 20 and 25. The value of volume flow rate of air was calculated for all air flow angle at different pressure difference to measure the feasibility of different angle at different pressure difference. Parametric analysis of air curtain is mainly categorized in to three different sections that are first when the outdoor and indoor pressure is same and air jet reaches the floor, this is called as optimum condition in which jet reaches the floor and trap the outflow and inflow. During the optimum condition there is some volume flow rate of air crosses the door which is may be due to air curtain placing on the top of the door which is reported by wang et.al [22]. During different pressure different cross that door, if air jet is able to reach the floor and restrict the infiltration and exfiltration that pressure range is called as a optimum pressure condition (ΔP_{oc}), which is difference ($P_o - P_i$) of outer and inner pressure. Where $P_o$the outside is pressure condition and P_o is the inside pressure condition. When outside pressure is higher as compared to inside pressure it is called as positive pressure difference and when the inside pressure is higher as compared to outside pressure it is called as negative pressure difference. Positive pressure difference after which outside air flow inside the system that is infiltration takes place is called as upper critical pressure difference (ΔP_{uc}), whereas the negative pressure difference after which exfiltration take place is called at the lower critical pressure difference (ΔP_{lc}).

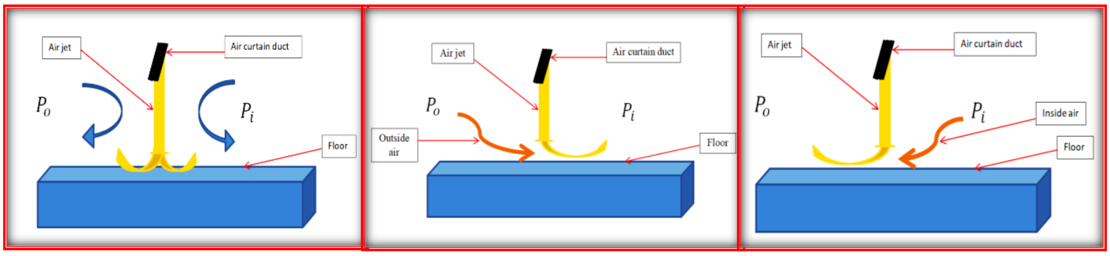

Fig.7 Shows (a) optimum condition during air curtain jet (b) the infiltration condition during air curtain jet (c) the exfiltration condition during air curtain jet

The velocity contours at different pressure air supply angle is shown in the below fig.

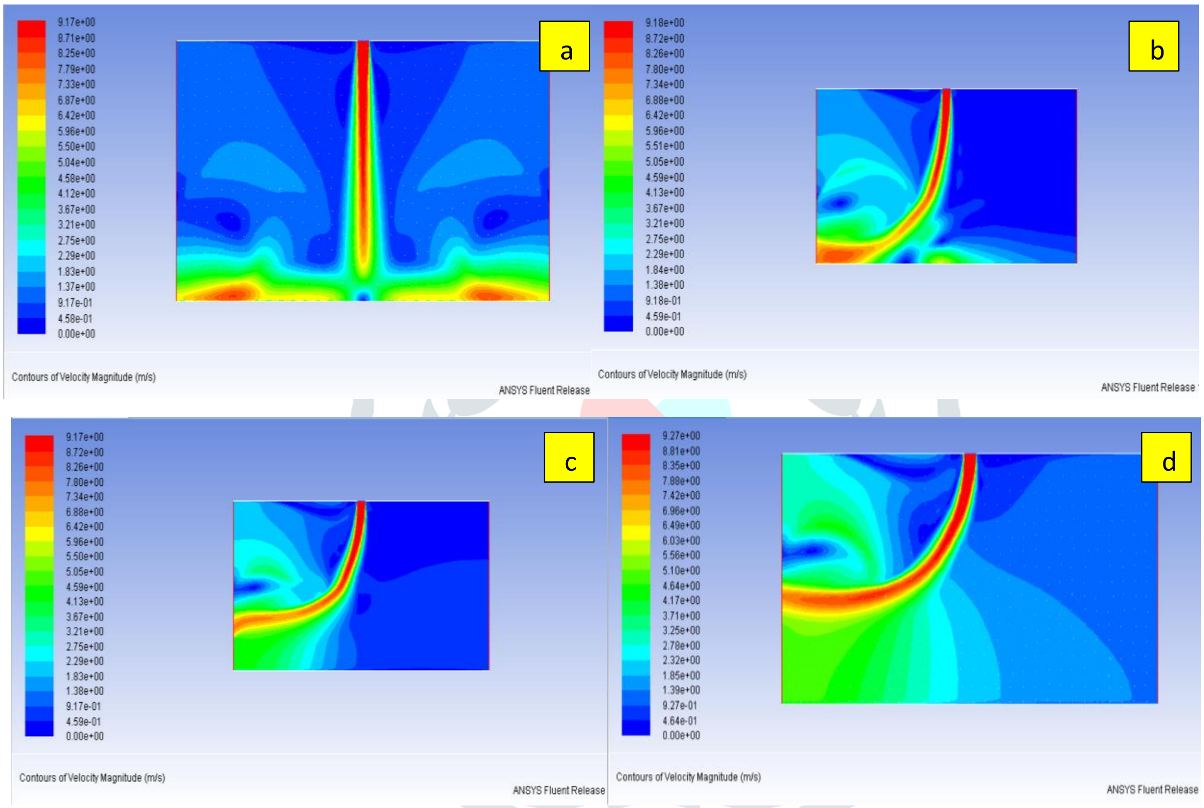

Fig.8 shows the contours of air jet (a) at 0 Pa pressure difference, (b) At -4 Pa pressure difference, (c) at -8 Pa pressure difference and (d) At -12 Pa pressure difference

7.1 Comparison of Different Air Flow Angle

In order to find the optimum air supply angle, comparison of volume flow rate of air for different supply angle were done and analyzed the most effective air supply angle. Through CFD analysis of air curtain volume flow rate of air through door during different pressure difference were calculated and compare in the below figure.

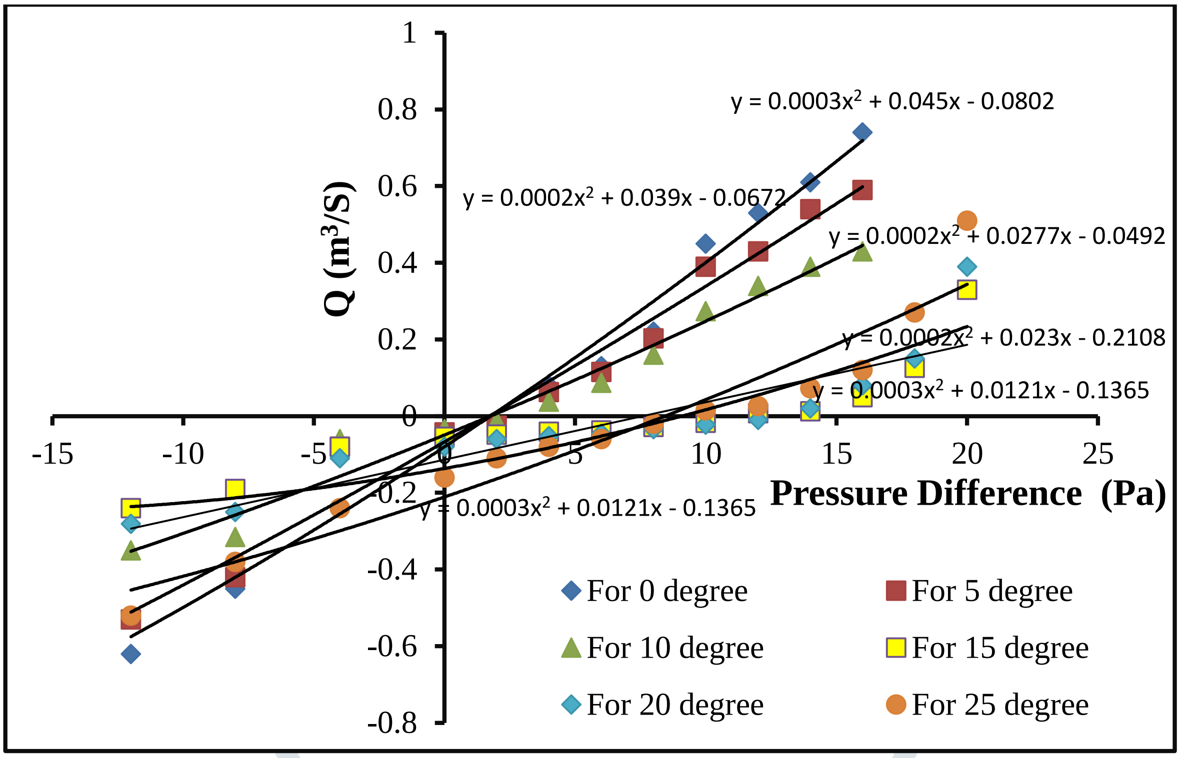

Fig.9 comparison of different air supply angle at different pressure difference

Through graph it is found that the air infiltration increases more frequently as pressure difference increases for 0 and 5 degree air supply angle. The air jet for 0 and 5 degree supply angle were not able to restrict the intrinsic flow after 5 Pa pressure difference, whereas during the negative pressure zone it also not able to restrict the extrinsic flow after 3.5 Pa pressure. There is slight flow of air during the negative pressure zone for 0 and 5 degree air supply angle during up to -5 Pa pressure difference whereas during same positive pressure difference that is 5 Pa flow rate is high which means more intrinsic flow. As the air supply angle increases from 5 degree to 15 degree it is found that as the supply angle increases both that is lower critical pressure difference and higher critical pressure difference increases. Increase in critical pressure shows that increasing supply angle is beneficial for the air curtain. Which means that there is a wide range of pressure difference in which air curtain restrict the flow of air across the door, but it is also observed that as the air supply angle increases from 15 degree to 20 degree it is observed that volume flow rate of air increases slightly as compared to 15 degree air supply angle.

8. Effect of Air Supply Speed on the Performance of Air Curtain

Here in this section it analyzed the effect of different velocity of air jet coming from the air curtain at different pressure difference. During the analysis here it considered same 2D plane dimension as considered in the above section. To analyze the effect of different velocity of air jet, here it considered six different velocity of air jet that is 5, 7, 9, 11, 13 and 15 m/s which is analyzed at different pressure difference that is -12, -8, -4, 0, 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20 Pa. During the CFD analysis of air curtain at different velocity of air jet other boundary conditions were same as considered in the above section analysis. The velocity contours for 5 m/s air jet speed is shown in the below fig. at different pressure difference.

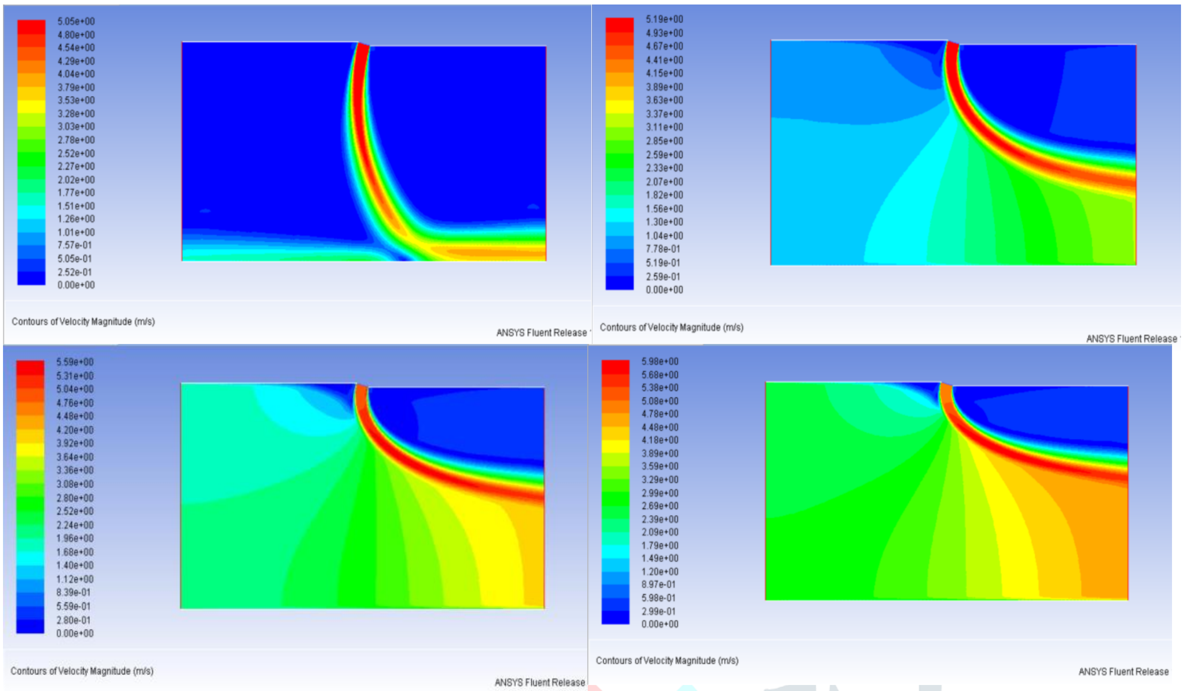

Fig.10 contours of velocity jet for 5 m/s velocity (a) at 2 Pa pressure difference, (b) at 6 Pa pressure difference, (c) at 10 Pa pressure difference and (d) at 14 Pa pressure difference.

8.1 Comparison of different velocity of air jet

For parametric evaluation of effect of air jet velocity on air curtain performance, here in this work it compares different velocity air jet at different pressure difference. In order to evaluate the effect of increase in supply angle on increase in velocity of air jet here it considered two air supply angle that is 15 and 20 degree. For each supply angle volume flow rate of air were calculated for different velocity at different pressure difference. The comparison of different velocity of air at particular supply angle is shown in the below figure.

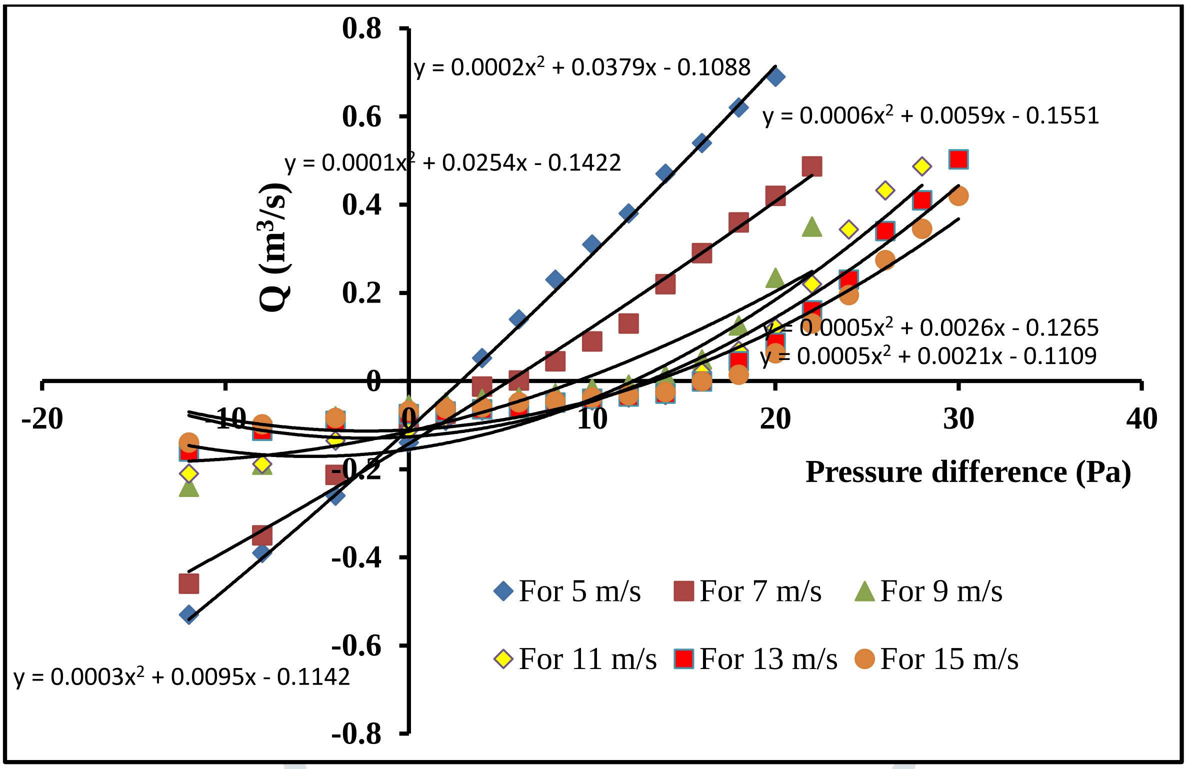

Fig.11 Comparison of different velocity of air jet at different pressure difference across the door for 15 degree air supply angle.

Through analysis it is found that the value of volume flow rate of air for air curtain at supply angle 15 degree shows the wide variation with respect to change in velocity of air jet as shown in above graph. Through analysis it is found that for 5 m/s velocity of air jet, upper critical pressure difference is very low, it is up to 2 Pa. which means it is able to restrict the flow of air or intrinsic flow only up to 2 Pa pressure difference. With velocity 7 m/s of air jet air curtain shows the same behaviour as shown for 5 m/s, there is marginally increase in upper critical pressure value. The change in variation of volume flow rate of air across the door at different negative and positive pressure difference is less for 5 and 7 m/s velocity of air jet, whereas it is higher for 9, 11,13 and 15 m/s velocity of air jet. The change in volume flow rate of air with respect to pressure difference across the door follow the polynomial distribution equations as mention in the graph. Through equations it is found that the variation sensitivity of volume flow of air with change in pressure difference is high in case of 5 and 7 m/s velocity of air jet. Whereas as for 9, 11, 13 and 15 m/s air jet velocity the variation sensitivity of volume flow rate of air with respect to pressure difference is less, which shows that change in pressure difference across the door is making more impact during low velocity jet. Whereas during high velocity jet change in pressure difference across the door make low impact on volume flow rate of air, which means the curve shift to the right with increase of supply velocity.

9. Conclusion

The CFD analysis of air curtain is the most efficient and less time consuming process for the analysis of the system as compared to experimental analysis. During experimental work due to some limitations like money and time each and every parameters where not analyzed in a deep. Increase in air supply angle increases the optimum pressure difference range means it increases the range in which air curtains were able to trap the intrinsic and extrinsic flow of air. It is found that the air infiltration increases more frequently as pressure difference increases for 0 and 5 degree air supply angle. Increase in critical pressure shows that increasing supply angle is beneficial for the air curtain, which means that there is a wide range of pressure difference in which air curtain restrict the flow of air across the door. Therefore through CFD analysis it is conclude that the value of volume flow rate is minimum for 15 degree air supply angle and with this angle the air jet at 9.1 m/s speed is able to restrict the flow of air up to 10 Pa positive pressure difference.

Through analysis it is found that with increase in air supply velocity increases the upper critical pressure difference ΔP_{uc} and decreases the value of lower critical pressure difference. It shows that change in air supply velocity shows wide variation in volume flow rate of air. The change in variation of volume flow rate of air across the door at different negative and positive pressure difference is less for 5 and 7 m/s velocity of air jet, whereas it is higher for 9, 11, 13 and 15 m/s velocity of air jet.

References

[1]. Joao Carlos Viegas, Fernando Oliveira and Daniel Aelenei [2018],” Experimental Study on the Aerodynamic Sealing of Air Curtains”, Fluids 2018, 3, 49; doi: 10.3390/fluids3030049.

[2]. D. Frank, P. F. Linden [2016], “The effects of an opposing buoyancy force on the performance of an air curtain in the doorway of a building”, Preprint submitted to Energy and Buildings.

[3]. Ran Gao, Angui Li, Wenjun Lei, Yujiao Zhao, Ying Zhang, Baoshun Deng, “Study of a proposed tunnel evacuation passageway formed by opposite-double air curtain ventilation” Safety Science 50 (2012) 1549–1557.

[4]. Zhou Dan, Tian Hong-q, Zheng Jin-li, Yan Xin [2015], “Smoke movement in a tunnel of a running metro train on fire”, DOI: 10.1007/s11771-015-2511-0.

[5]. D. Frank and P. F. Linden [2014], “The effectiveness of an air curtain in the doorway of a ventilated building”, J. Fluid Mech. (2014), vol. 756, 130164., doi:10.1017/jfm.2014.433.

[6]. Mr Nitin Kardekar, Dr. V K Bhojwani, Dr Sane N K [2013], “experimental performance analysis of flow of air curtain”, International Journal of Mechanical Engineering and Technology (IJMET), ISSN 0976 –6340(Print), ISSN 0976 – 6359(Online) Volume 4, Issue 3, May - June (2013) © IAEME.

[7]. Adam Cowlard, Adam Bittern, Cecilia Abecassis-Empis, Jos Torero [2013], “Fire safety design for tall buildings”, Procedia Engineering 62 (2013) 169 – 181.

[8]. Sijie Fu, Pascal Henry Biwole, Christian Mathis [2013], “Particle Tracking Velocimetry for indoor airflow field: A review”, Department of mathematics and interactions, CNRS UMR 7351.

[9]. Tomas Gil-Lopez, Juan Castejon-Navas, Miguel A. Galvez-Huerta, Paul G. O'Donohoe "Energetic, Environmental and Economic Analysis of Climatic Separation by means of Air Curtains in Cold Storage Rooms" http://dx.doi.org/doi:10.1016/j.enbuild.2014.01.026.

[10]. Christian Diaz-Ovalle, Richart Vazquez-Roman, Raul Lesso-Arroyo, M. Sam Mannan. "A simplified steady-state model for air, water and steam curtains". Journal of Loss Prevention in the Process Industries 25 (2012) 974e981.

[11]. Jialei Zhang, Xiaodong Zhou, Qinkun Xu, Lizhong Yang [2012], "The inclination effect on CO generation and smoke movement in an inclined tunnel fire", Tunnelling and Underground Space Technology 29 (2012) 78–84.

[12]. Zhiqiang (John) Zhai, AnnaL,Osborne [2012], "Simulation-based feasibility study of improved air conditioning systems for hospital operating room", Frontiers of Architectural Research(2013) 2, 468–475.

[13]. Yang-Cheng Shih, An-Shik Yang, Chang-Wei Lu. "Using air curtain to control pollutant spreading for emergency management in a cleanroom". Building and Environment 46 (2011) 1104e1114.

[14]. Julian Ernesto Jaramillo Ibarra [2008], "Suitability of Different RANS Models in the Description of Turbulent Forced Convection Flows. Application to Air Curtains", In Refrigeration and Air Conditioning Conference, 2008.

[15]. F. Felis, M. Pavageau, J.C. Elicer-Cortés, T. Dassonville, [2010], "Simultaneous measurements of temperature and velocity fluctuations in a double stream-twin jet air curtain for heat confinement in case of tunnel fire", International Communications in Heat and Mass Transfer 37 (2010) 1191–1196.

[16]. Sanjeev Gupta, Michel Pavageau, Juan-Carlos Elicer-Cortes, Cellular confinement of tunnel sections between two air curtains, Building and Environment 42 (2007) 3352–3365.

[17]. Long-Xing Yu, Tarek Beji, Georgios Maragkos and Bart Merci [2018], "Assessment of Numerical Simulation Capabilities of the Fire Dynamics Simulator (FDS 6) for Planar Air Curtain Flows", doi.org/10.1007/s10694-018-0701-7.

[18]. L. (Leon) Wang, Z. Zhang [2016]," An approach to determine infiltration characteristics of building entrance equipped with air curtains", Energy Build. 75 (Jun. 2014) 312e320.

[19]. Long-Xing Yu, Tarek Beji, Georgios Maragkos and Bart Merci [2016], "Assessment of Numerical Simulation Capabilities of the Fire Dynamics Simulator (FDS 6) for Planar Air Curtain Flows", doi.org/10.1007/s10694-018-0701-7.

[20]. Nie Wen, Liu Yanghao, Wei Wenle, Hu Xiangming, Ma Xiao, Peng Huitian. "Effect of suppressing dust by multi-direction whirling air curtain on fully mechanized mining face". International Journal of Mining Science and Technology xxx (2016) xxx–xxx.

[21]. Liangzhu (Leon) Wang, Zhipeng Zhong [2014], "An approach to determine infiltration characteristics of buildingentrance equipped with air curtains", Energy and Buildings 75 (2014) 312–320.

[22]. L. (Leon) Wang, Z. Zhong [2014]," Whole building annual energy analysis of air curtain performance in commercial building", in: eSim, 2014.

[23]. Chao Cheng, Wei Tan, Liyan Liu, "Numerical simulation of water curtain application for ammonia release dispersion", Journal of Loss Prevention in the Process Industries 30 (2014) 105-112.

[24]. Felipe Vittori, Luis Rojas-Solórzanoa, Michel Pavageau [2012], "Response Surface Methodology for Analysis of an Air Curtain Used as Emergency Ventilation System in a Tunnel Fire", VOL. 26, 2012 DOI. 10.3303/CET1226067.

[25]. Grzegorz Krajewski, Grzegorz Sztarbala [2011], "air curtains used for separating smoke free zones in case of fire", 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November.