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Interaction of a Complex Ventilation Network with a

Confined Room Fire: Application to Nuclear Facilities

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International Master of Science in Fire Safety Engineering

Disclaimer

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Read and Approved

(Nikhil Verma)
30th April, 2017.

Abstract

In nuclear facilities, compartments are generally sealed from one another and connected through a complex ventilation network. In normal operating conditions, such network ensures a dynamic confinement through a pressure cascade that prevents the release of hazardous materials to the atmosphere. In the event of a fire in a confined room, the pressure increases because of the release of hot combustion products. The ventilation conditions are thus altered. In this thesis work, the interaction between a complex ventilation network and a fire has been studied numerically using a Computational Fluid Dynamics (CFD) code, namely the Fire Dynamics Simulator (FDS6). This work is a part of an international research program called PRISME.

The work of the thesis has been divided into two parts. In first part of work, the set-up and validation of given ventilation network and available experimental data has been done (without fire) using FDS 6. After proper validation of HVAC set-up, ventilation system interaction with fire in the room has been studied. Here the purpose has been to study the pressure and volumetric flow rate profile with the effect of fire on them in FDS and to check if FDS is able produce the same pressure and volumetric flow rate profile as recorded in the experiment. Sensitivity studies have also been done for various input parameters for HVAC in FDS.

A complex ventilation network (without fire effects) with fans having constant volume flow characteristics has been successfully validated in FDS. Moreover, a simple ventilation network with quadratic characteristics fans having fire effects has also been validated, which also substantiates the FDS capability to model ventilation network having the effects of a fire.

Abstract (Hindi)

परमाणु सुविधाओ में विभिन्न भागो (कमरे) को सामान्य तौर पर एक दुसरे से अलग बंद रखा जाता है ओर उन्हे जटील वायु सन्चालन के माध्यम से जोड़ा जाता है । सामान्य परिचालन स्थितियों में, ऐसे नेटवर्क एक दबाव के माध्यम से एक गतिशील कारावास सुनिश्चित करता है जो कमरे के बाहर के वातावरण में खतरनाक सामग्री के रिलीज को रोकता है। एक सीमित (बंद) कमरे में आग लगने की स्थिति में गर्म जवलनशील उत्पादो के बनाने के कारण दवाव बढ जाता है । वायु सन्चालन की स्थिति इस प्राकर बदल जाती है । इस शोध कार्य में जटिल वायु सन्चालन नेटवर्क और आग के आदान-प्रदान को संख्यात्मक रूप से सीएफडी कोड अर्थत एफडीएस6 (FDS6) का उपयोग करते हुए अध्ययन किया गया है। यह कार्य एक अंतर्राष्ट्रीय अनुसंधान कार्यक्रम का हिस्सा है जिसे पीआरएसएमई (PRISME) कहा जाता है।

इस शोध कार्य को दो भागों में विभाजीत किया गया है। पहले भाग में वायु संचालन को कमरो में कायम रखा गया है और उसकी पुष्टी उपलब्ध प्रयोग डाटा को एफडीएस6 (FDS6) में प्रयोग करते हुए किया गया है (बिना अग्नि के) । एचवीएसी (HVAC) सेटअप के उचित पुष्टी के बाद वायु संचालन को कमरे में आग के आदान- प्रदान के साथ अध्ययन किया गया है। यहाँ पर अध्ययन का उद्देश्य एफडीएस (FDS) में आग के प्रभाव के साथ दवाव और वॉल्यूमेट्रिक बहाव के रुपरेखा का अध्ययन करना है और यह जांचने के लिए कि क्या एफडीएस प्रयोग में रिकॉर्ड किए गए समान दबाव और वॉल्यूमेट्रिक फ्लो रेट प्रोफ़ाइल का उत्पादन कर पाता है। एफडीएस में एचवीएसी के विभिन्न इनपुट पैरामीटर के लिए संवेदनशीलता अध्ययन भी किया गया है।

एफडीएस में निरंतर मात्रा प्रभाव पेरामीटर वाले पंखे के साथ एक जटिल वैटिलेशन नेटवर्क (बिना आग प्रभाव के) को आवंटित करते हुए सफलतापूर्वक पुष्टी की गई है। इसके अलावा एक सरल वैटिलेशन नेटवर्क (आग के प्रभाव के साथ) जिसमे द्विघात पंखे का प्रयोग किया गया है उसको भी आवंटित किया गया है, जो आग के प्रभाव के साथ वेंटिलेशन नेटवर्क मॉडेलिंग के लिए एफडीएस क्षमता को भी सिद्ध करता है।

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I. Introduction and Objectives

I.1 Introduction

Nuclear plants are one of the prominent source of energy in our present day life. But such plants have high potential to cause catastrophic harm if any damage happens to the nuclear reactor core where nuclear reactions take place. Fire in nuclear installations have significant potential to contribute directly or indirectly to the risk which can cause damage to nuclear reactor core. The likelihood at which the core can get damaged is generally referred as core damage frequency and fire remains one of its main contributor [1]. Any damage to nuclear core will prevent the control of nuclear reactions which will lead to uncontrolled nuclear chain reactions. This will cause havoc not for only the installation but also to the nearby area of the installation and human life. So it becomes extremely important to understand the behaviour of fire in a nuclear facility and to limit it damaging effects to the minimum extent possible.

The environmental setup in a nuclear plant is very different from a normal residential, commercial or industrial building. Rooms in nuclear facilities are well compartmented and sealed from each other by walls and doors, and at same time connected to each other through a complex ventilation network of inlet and outlet ducts. A sample set up of rooms is shown in figure 1.

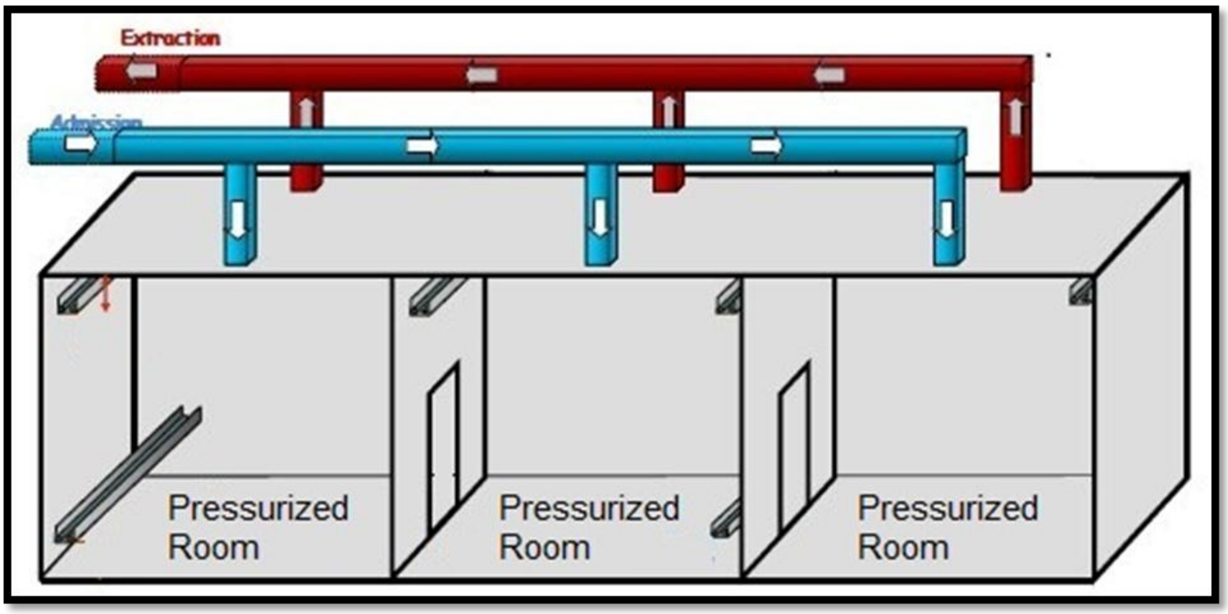


Figure 1. Sample room set-up in a nuclear facility. (Picture taken from OECD/NEA PRISME Project Application Report, NEA/CSNI/R (2012)14, Modified)

The setup has three rooms adjacent to each other and are separated from each other through walls having fire doors. Inlet lines are shown in blue colour as admission lines and outlet lines are shown in red colours as extraction lines. Arrow represents the direction of flow.

With such set-up, there exists a strong correlation between fire and ventilation conditions. In normal operating conditions, such duct network with almost perfectly sealed rooms through pressurization, walls and doors leads to the development of pressure cascade that helps to prevent the release of hazardous materials in case of accidents not only related to fire but also due to radioactive materials. In an event of a fire in a room, the pressure increases in the room due to release of hot combustion products, and the ventilation conditions gets altered for a period of time as smoke starts to enter the inlet duct. Due to change in the direction of flow in ducts which happens for a period of time, the heat release rate of fire starts to decrease after a while due to the limitation of the air supply as no air is coming from inlet point. With decrease in heat release rate due to oxygen deficiency the pressure in the room decreases and the induction of air again starts in the room which re-vitalize the fire and increases its heat release rate. The subsequent gradual dip and shoot in heat release rate is observed in a cyclic pattern and affects the ventilation network in tandem with prevailing heat release rate at the moment. Due to overpressure in the room, hot smoke enters the inlet duct and contaminate the other rooms connected by ducts (shown in Figure 1.). This phenomena of reverse flow due to complex interaction between heat release rate and ventilation system poses danger to the safety of the installation in terms of both life safety and equipment safety by toxic effects and thermal stresses respectively.

I.2 Objectives

In this thesis work, it is aimed to numerically study the complex interaction between a ventilation network and a fire in a nuclear installation using Computational Fluid Dynamics (CFD) code, namely the Fire Dynamics Simulator (FDS) (Version 6). This work is a part of an international research program called PRISME project. The abbreviation “PRISME” comes from the French phrase *propagation d’un incendie pour des* scénarios multi-locauxélémentaire, which means "fire propagation in elementary multi-room scenarios". This project consists of a series of fire and smoke propagation tests in a dedicated built facility built at the French *Institut de radioprotection et de sûreténucléaire* (IRSN) centre at Cadarache, France. Data generated from various tests covers room to room heat and smoke propagation, effects on ventilation system and resulting thermal stresses on sensitive equipment. The data is used in this thesis in order to assess the capabilities of the CFD code FDS to simulate the fire and ventilation interaction in a confined but mechanically ventilated room setup [1][2].

Firstly, a simple and complex ventilation network is set up in FDS and validated with available experimental HVAC (Heat, Ventilation and Air Conditioning) data. In this case no fire is considered. Once proper validation of HVAC set up is done then we move to the second step. In this step, the analysis of the interaction of the ventilation network for a room fire is done. Here, the main objective is to assess the volume flow rates and pressure profiles in FDS, which will be changing with fire behaviour with time. The values of various variable like volume flow rate and pressure is checked to match the experimental data. This will help to testify the capability of FDS to satisfactorily simulate the fire in a confined room being mechanically ventilated.

By “validation”, it is meant that the models in FDS are checked to find out whether it accurately represents the real world from the view of the intended uses of the model or not. It is like solving the right equations in CFD and getting the simulations representing the real world of which experimental data are available [3].

II. Numerical modelling using FDS

In this section, a brief description about FDS and its hydrodynamic solver has been done. Moreover, HVAC solver coupled to FDS has been described in details along with its limitations.

II.1 Computational Fluid Dynamics (CFD)

Fire has always intrigued humans. The urge to understand the behaviour of fire and its various effects has led to tremendous development in the fire science. Fire science together with the powerful computers available at reasonable cost, great progress has been made to predict the fire phenomena and its effects. The fluid flow caused by fire is complex in nature but the fundamental laws of mechanics of fluid can be applied to them to predict their properties. The fluid flow can be described by the sets of non-linear partial differential equations (Navier-Stokes Equations) covering the conservation of mass, momentum and energy as follows:

Conversation of mass

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0 \qquad (1)$$

Conversation of momentum

$$\frac{\partial}{\partial t}(\rho u) + \nabla.\rho u u + \nabla p = \rho f + \nabla \cdot \tau_{ij} \qquad (2)$$

Conversation of energy

$$\frac{\partial}{\partial t}(\rho h) + \nabla.\rho h u = \frac{Dp}{Dt} + q^{m} - \nabla.q \qquad (3)$$

Where, $\nabla = \frac{\partial}{\partial x}\,\mathrm{i} + \frac{\partial}{\partial y}\,\mathrm{j} + \frac{\partial}{\partial z}\,\mathrm{k}$, u= velocity vector field, p = pressure, T = temperature, ρ = density, τ_{ij} is shear stress, f is the external force, q''' is the energy produced, q is net radiation energy, h is the enthalpy.

Right now it is not possible to solve these equations analytically for fluid flows but it is possible to get an approximate computer based solution by numerically solving them for the case in consideration. This is the area of Computational Fluid Dynamics (CFD) where numerical methods are developed to solve non-linear partial differential equations.

The computational domain that represents the environment to be simulated with CFD is divided into small control volumes called grid cells. Thus CFD replaces the continuous problem domain with a non-continuous domain called discrete domain where flow variables are defined only at grid points or cell's faces which has its nodes/corners along discrete points [4] [5]. The equations of conservation of mass, momentum and energy are applied to control volumes defined by cells and are discretised over cells to get the set of coupled algebraic equations in the discrete variables. The algebraic equations along with boundary conditions is required to be solved to get the desired solution. Such equations involve large number of repetitive calculations which are intense and time taking. All such equations are put in matrix form and solved using present day computers. Thus computational fluid dynamics is about computational method of numerically solving Navier-Stokes Equations.

Simulating a fire is not an easy task. Combustion model, thermal radiation model, flame spread model, soot model etc. made must be carefully chosen to simulate the fire case in consideration. Fire fluid flow being buoyancy driven turbulent flow makes the simulation more challenging as turbulence is one of the most challenging aspect to model. There are three available techniques for the treatment of turbulence: Reynolds-Averaged Navier Stokes (RANS) model, Large Eddy Simulation (LES) model and Direct Numerical Simulations (DNS) model.

In RANS model, Navier-Stokes equations are time averaged for all length scales considered. The assumption is that any quantity's instantaneous value can be decomposed into time averaged value and fluctuating value. In case of DNS, all relevant scales are resolved which are occurring in the flow. This approach is not of practical use for simulating building fire as it requires extremely fine mesh and takes lot of time. No further discussion about RANS and DNS is done in this thesis. LES approach is described in FDS section.

II.2 Fire Dynamics Simulator and Hydrodynamic Solver

FDS is a computational software developed by National Institute of Standards and Technology USA and VTT Technical Research Centre of Finland. It is a CFD model of fire-driven fluid flow. It solves a form of Navier-Stokes equations appropriate for low speed (Mach Number< 0.3), thermally driven flow with an emphasis on smoke and heat transport from fires. FDS has been developed with an aim to deal with practical fire problems in fire protection engineering along with the scope to study fundamental fire dynamics and combustion [6].

II.2.1 Important Features of FDS

Hydrodynamic Model-As mentioned above, FDS solves Navier-Stokes equation for fire phenomena. The applicable equations are discretised over cells in the computation domain and an explicit predictor-corrector scheme with second order accuracy in time and space is used. LES model is used for turbulence which is also the default mode. Here only the large scale eddies are resolved and small eddies below mesh size are filtered out and modelled. The mesh size is the main factor to determine the size of eddies resolved.

Flow of smoke is seldom laminar and most of the time it is turbulent flow. In the case of turbulent flow, the mixing is not only due to molecular diffusion but also due to eddies formation. Here the turbulent shear stress at scales of eddies becomes the sub-grid scale term and can only be modelled so that we can solve momentum transport equation. The turbulent shear stress which is dependent on turbulent viscosity is modelled by various set of equations. In FDS6, the Deardorff turbulent viscosity equation is used which is as follows:

$$\mu = \rho C_v \Delta \sqrt{k} \qquad (4)$$

where, μ is the turbulent viscosity, ρ is the density of fluid, C_v= 0.1 and k is the sub-grid scale kinetic energy. Δ is the LES filter width which is equal to geometric mean of local mesh spacing in each direction as $\Delta = (\delta x \delta y \delta z)^{1/3}$, where δx, δy, δz are the dimensions of the smallest mesh cell [6][7].

Combustion Model- For most applications, FDS uses a single step, mixing-controlled chemical reaction with lumped species air, fuel and products. In this approach fuel and oxygen react infinitely fast to create combustion products. The mixture fraction model generally used in CFD is based on this approach. The mixture is the conserved scalar quantity which computes the fraction of gas at a given point in the flow field that originated as a fuel.

Radiation Transport- Radiative heat transfer is included in the model through the solution of radiation transport equation for a gray gas [9], and in some limited cases wide band model is also used. The method is known as Finite Volume Method [FVM] as the technique is similar to finite volume methods for convective transport.

II.2.2 Methodology of Simulation Setup in FDS

In order to setup a simulation, with and without fire, all the parameters, boundary conditions, and domain setup should be done keeping in mind the limitations and computing process of FDS. The effects of default conditions should be studied and outlined first. Default values should be changed in cases where they do not match the given test conditions and data. Moreover, parameters for the simulation should be set in such a way that there is not unnecessary delay in the computation and at the same time the results obtained are reliable.

Time of Simulation and Time Step- The time of the simulation is kept in such a way that steady conditions are reached if it is expected. The time step for the calculation has been kept as default value and is adjusted in FDS satisfying the Courant, Friedrichs, Lewy conditions (CFL).The CFL constraint is given by

$$\mathrm{CFL} = \delta\left(\frac{[\mathrm{u}]}{\delta \mathrm{x}}\right) < 1 \qquad (5)$$

which physically means that a fluid element should not transverse more than one cell within a time step. This will ensure that in order to resolve an eddy of size δx, the time step should obey the CFL constraint. Here, δt is the time step and u is the velocity of the flow in the cell [7]. This is left default to reap the benefits of LES in FDS.

Cell Size and Cell Numbers- The computational mesh in FDS is made in such a way that as far as possible the mesh cells resemble a cube in each simulations thus avoiding aspect ratio getting more than 2:1 and as an important part of the calculation uses a Poisson solver based on Fast Fourier Transforms in the y and z directions, the second and third dimension of the mesh is kept in the form as $y = 2^l 3^m 5^n$ and $z = 2^l 3^m 5^n$, where l, m, n are integers. This is done to avoid unduly slow calculation and numerical instability errors.

Mesh Resolution and Sensitivity Study- Mesh resolution have the most influential impact on FDS results. In case when no fire is involved, first the simulation file has been built with relatively coarse mesh and gradually refined until no appreciable difference is noted in the results. This is referred as a mesh sensitivity study.

In case of fire simulations, the characteristic fire diameter D* has been calculated as

$$D^* = \left(\frac{Q}{\rho C p T \sqrt{g}}\right)^{2/5} \qquad (6)$$

where, Q is the total heat release rate of the fire, ρ is the density of the air, C_p is the specific heat at the constant volume, and T is the ambient temperature.

The value of D*/δx which ranges from 4 to 16, gives the measure of how well the flow field is resolved [6], where δx is the cell size in x-direction.

The simulations have been done with D*/δx in the range of more than 4 and progressed towards 16 until we get a stable, non-varying result.

Boundary Conditions-The back ground pressure, ambient temperature and noise has been kept as default values as 101325 Pa, 20 degree Celsius and 0.005 m/s respectively in FDS.

All the obstruction created in the domain is approximated in rectangular shape and is forced to conform to underlying grid by default.

The boundary conditions for walls and other obstructions have been chosen by using the proper name lists defining material properties on solid obstructions and surface properties defining obstruction's layer thickness, sections of layers, backing etc. These properties along with condition chosen (INSULATED/VOID/EXPOSED) for back side of wall (side of wall which is not exposed to fire) is used by 1D solid phase thermodynamic solver in FDS to compute heat transfer. The thickness of all wall has been kept 0.1m in all cases as obstruction's thickness is not involved in heat transfer phenomena but just acts as an obstruction to fluid flow.

II.3 FDS and HVAC (Heat, Ventilation and Air Conditioning) Solver

Earlier versions of FDS had limitations and could model fairly simple HVAC system and had no coupling of mass, momentum and energy solutions amongst multiple outlets and inlets of a HVAC network. The present version of FDS (FDS6) has HVAC network solver coupled to it. The HVAC solver is based on MELCOR thermal hydraulic solver which is a computer program used to simulate accidents in nuclear power plant buildings [7]. With numbers of verification trails [8], it has been demonstrated that HVAC network solver correctly models the HVAC flows and its coupling with FDS maintains mass conservation. It has also been demonstrated that FDS with HVAC solver accurately predicts HVAC flows for a duct network in a complex geometry with fire effects [10].

II.3.1 HVAC Models

Conservation Equations

A HVAC system in FDS is represented as a network of ducts and nodes where nodes represent a point where either two or more ducts join together or duct joins the FDS domain (shown in figure 2). Nodes have no volume, and mass and energy conservation equation are merely that what flows into a node must also flow out of the node. The current model does not account for the mass storage within the HVAC network.

The conservation equations are:

Mass: $\sum \rho_j \, u_j \, A_j = 0$ (7)

Energy: $\sum \rho_j \, u_j \, h_j = 0$ (8)

Momentum: $\rho_j \, L_j \, \frac{du_j}{dt} = (p_i - p_k) + \rho g \Delta z + \Delta p_j - \frac{1}{2} \, K \rho_j |u_j| u_j$ (9)

where, u_j is the velocity in duct j, A is the duct cross-sectional area, and h is the enthalpy of the duct. Subscript j represents a duct, i and k subscript represent nodes. Δp represents the source of momentum (fan or blower), L is the length of the duct j, K is the friction loss in the duct. ρ is the density of the fluid and p_i and p_k represents the pressure at nodes i and k respectively [11].

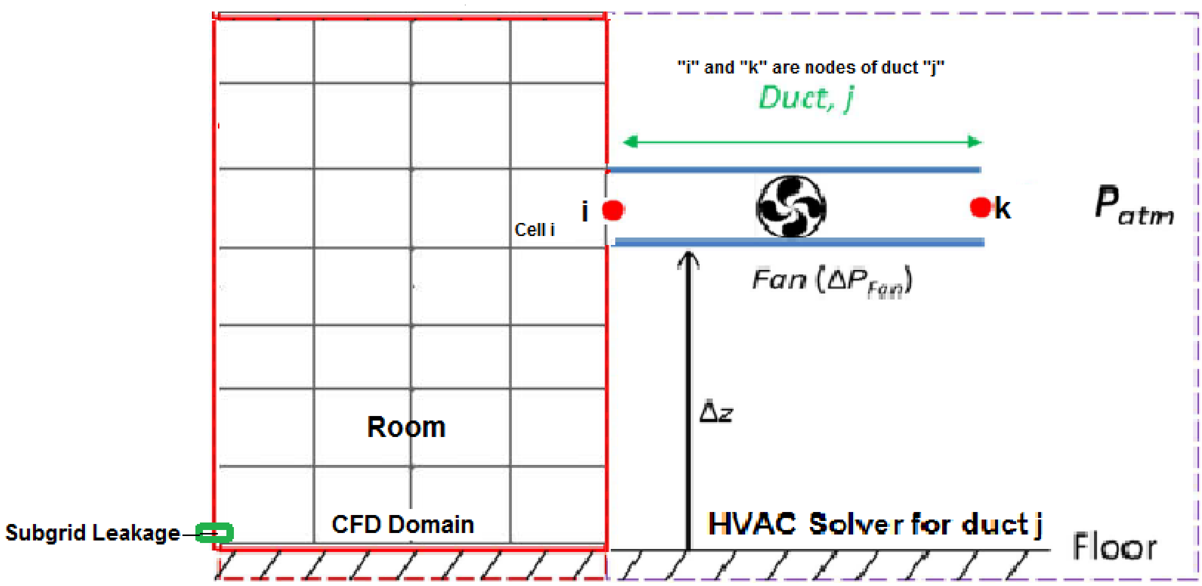


Figure 2. A duct connected to CFD Domain. (Taken from Classroom lecture slide of CFD Simulations by dr. Tarek Beji, Session 4, Modified)

In figure 2, HVAC duct is connected to a CFD domain through node "i" and other end of duct "k" is connected to ambient condition. Node equations for mass, momentum and energy is only solved for HVAC system. The pressure in the room depends on the mass and energy flow into and out of the room which is predicted by HVAC and CFD model. Sub-grid leakage is modelled here to use its effect in the calculation.

It is important to note that in reality HVAC model in FDS only simulates the movement of the flow accounting for the height difference which is Δz in the figure2. There is no consideration of heat transfer and transient movement of the smoke flow inside the ducts.

Basic Model for Pressure Rise in FDS

Within the computational domain, the space which is entirely surrounded by solid obstructions can be denoted as a pressure zone. For example, in nuclear plants the rooms are completely sealed from one another. So they can be assigned as different pressure zones. For each pressure zone, FDS divides the absolute pressure into a background pressure and a perturbation pressure which can be stated as follows [11]:

$$p = \bar{\boldsymbol{p}} + \tilde{\boldsymbol{p}} \qquad (10)$$

The background pressure which is computed for each zone, $\bar{\boldsymbol{p}}$ is used in the equation of state to correlate pressure with density and temperature:

$$\bar{p}(t) = \rho \bar{R} T \sum Y_i / M_i \qquad (11)$$

where, ρ is density (kg/m^3), R is gas constant (8.314 J/mol/K), T is temperature in K, Y_i is mass fraction and M_i is the molecular weight.

The perturbation pressure $\tilde{p}$, is only for the calculation of fluid momentum equation. In actual sense, the perturbation pressure has limited physical meaning. It is more like a term used for the correction of the velocity fields in the solution of the momentum equation [11].

II.3.2 Important Input Parameters for HVAC Simulation Setup in FDS

For all input parameters, FDS user guide [6] can be referred. Here some selected parameters are discussed, some of which involves manual calculations before putting their values in FDS code.

II.3.2.1 Pressure Zones and Leakages

FDS allows to build rooms with different pressure zones which can be leak free and also with leakages. A leak free room is not an ideal case. Small gaps can occur along doors, windows, at places where walls abut each other and places where a floor and a ceiling joins walls. In case of a fire, air and smoke will escape through these small gaps which can be termed as leakages [13].

Leakages are basically sub-grid phenomena because leakage areas are very small in size. In order to simulate leakages in FDS, a user defined volume within the computational domain surrounded by solid obstructions is defined as a pressure zone. For example, room shown in figure 3 can be assigned as a pressure zone in FDS and its area of leakages can be specified in codes. The HVAC solver in FDS will use the leakage area for the pressure zone and will consider the leak between two zones as to be a pair of HVAC vents connected by a duct with a loss coefficient of 1.

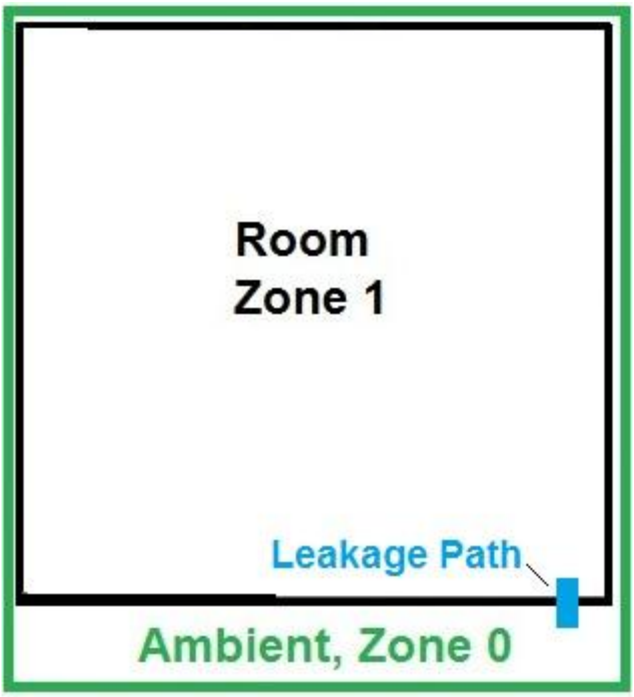


Figure 3. Room and Pressure zones.

In figure 3, Zone 0 is assigned to the external domain of CFD by default. As zone 1 is assigned to the room, the value of area of leakage between Zone 1 to Zone 0 is assigned in FDS to include leakages in the computation.

Model for volume flow $\dot{V}_{leak}$ through a leakage area A_L is as

$$\dot{V}_{leak} = A_L \cdot sign(\Delta p) \cdot \sqrt{2\frac{|\Delta p|}{\rho}} \qquad (12)$$

Where, Δp is the pressure difference between the adjacent pressure zones in Pa, ρ is the ambient density in kg/m^3. For more detail refer to [6].

II.3.2.2 Fan curves for Inlet and Exhaust Fans

In FDS, a fan can be put in a duct with a desired volume flow rate which can be constant or quadratic in nature or its volume flow rate can be user defined (ramping in FDS). In reality no fan behaves as with constant flow rate and its flow rate gets altered if its duct encounters a counter-pressure from the fluid flow which is opposite to the direction in which fan is designed to push fluid (air or gas). If a room is having an inlet vent and outlet vent then the pressure change (increase or decrease) in the room due to fire will alter the volume flow rate of the fan which would not be constant anymore. The volume flow rate in such cases becomes the function of change in pressure in the room or enclosure and can be expressed as follows:

$$\dot{V}_{fan} = f(\Delta p) \qquad (13)$$

where, $\dot{V}_{fan}$ is the volumetric flow rate of a fan which gets dependent on pressure.

The function f(Δp) can follow a polynomial function, a piece-wise linear function or could be user-defined function and is the fan characteristics [12]. As in reality fans operate based on pressure drop across the duct or manifold in which they are installed, the volumetric flow rate $\dot{V}_{fan}$ of a fan can be represented by simple “fan curve” given by

$$\dot{V}_{fan} = \dot{V}_{max} \cdot sign(\Delta p_{max} - \Delta p) \cdot \sqrt{\frac{|\Delta p - \Delta p_{max}|}{\Delta p_{max}}} \qquad (14)$$

where, $\dot{V}_{max}$ is the volume flow rate when pressure difference becomes zero, Δp_{max} is the maximum pressure difference at which fan can operate (Also called Stall pressure of fan), Δp is the difference in pressure between the downstream compartment and upstream compartment.

If the various values of pressure Δp is plotted against the $\dot{V}_{fan}$ as per given by the fan curve equation (14) then a fan curve similar to as shown in figure 4 can obtained.

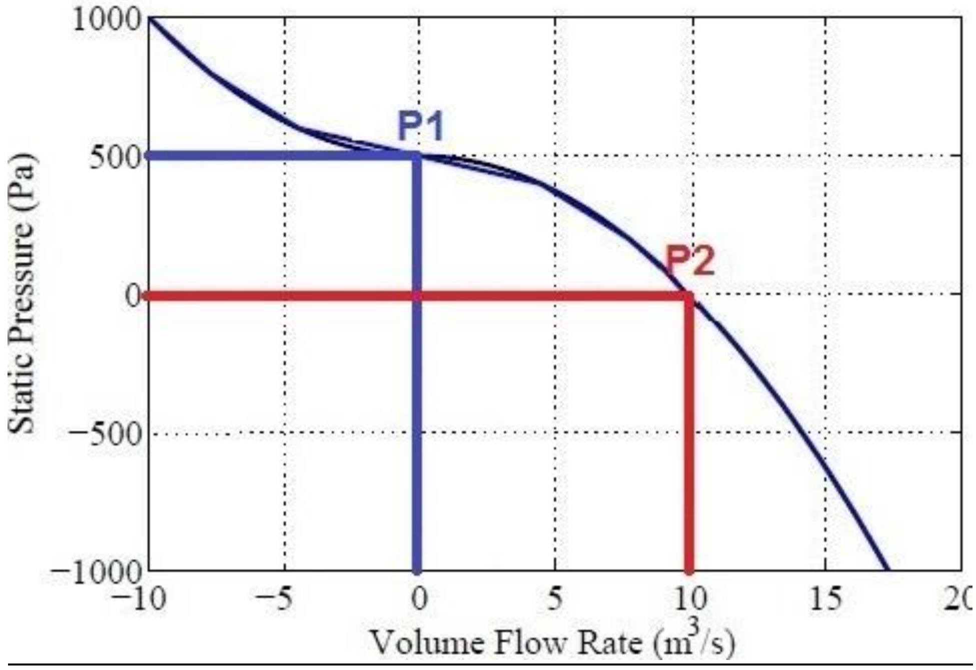


Figure 4. Fan curve with quadratic behaviour. (Picture taken from [6], pp-97, Modified)

From figure 4, it can interpreted from the curve that at point P1 the static pressure is 500 and at this pressure the volume flow rate becomes zero. The fan is not able to sustain the counter pressure at this point and stops to push fluid (air) in the designed direction. It can be also noted from the graph that if Point P1 moves leftward along the curve then flow reversal takes place at high static pressure and volumetric flow rate becomes negative. At point P2, the static pressure is zero and fan functions at its designed volumetric flow rate. If point P2 is moved rightward along the curve then it can be seen that the static pressure gets below zero and then the volumetric flow rate starts to increase as negative pressure develops in the duct and fan can easily push more fluid (air) in the designed direction. For more detail refer [12].

In order to write the code in FDS for a quadratic fan, the value of $\dot{V}_{max}$ and Δp_{max} are required. In the case of fire, if there is the data of pressure rise against the volumetric flow rate in the duct having the ventilation fan then such data has to be graphically analysed to spot the quadratic curve among the scattered data and to extract the values for stall pressure and max volumetric flow rate. With few hit and trails one can replicate the fan curve in FDS. For examples of curve fitting refer [12] and section III.2.3.

II.3.2.3 Loss Coefficient for Duct

A HVAC network can have multiple nodes and ducts comprising bend, valves and other components. In order to model a duct, its node’s pressure and volumetric flow rate in it is required to calculate a factor called Loss Coefficient [13]. Consider a duct j having two nodes “i” and “k” in figure 2.

Pressure at node i = P_i, Pressure at node k = P_k, Area of the duct = A m^2, Volumetric flow rate in duct = V m^3/s.

Then Loss Coefficient K,

$$K = \frac{2 \cdot \Delta P_{nodes}}{\rho_{air} \cdot u_{duct}^2} \qquad (15)$$

Where $\Delta P_{nodes} = P_i - P_j$ Pa, ρ_{air} = density of air kg/m^3, u_{duct} = velocity of flow in duct = $\frac{V}{A}$ m/s

The value of K is taken as an absolute value and feed in the codes of FDS.

In case of a duct having multiple node points, loss coefficient of each duct part between two nodes are calculated (figure 5). The final equivalent duct is of same length of the whole duct but its equivalent area A_{eff} or diameter is chosen and overall loss coefficient K_{eff} is calculated as follows

$$K_{eff} = \sum_i K_i \frac{A_{eff}}{A_i} \qquad (16)$$

Where i is a duct fitting and A_i is the area associated with the fitting loss.

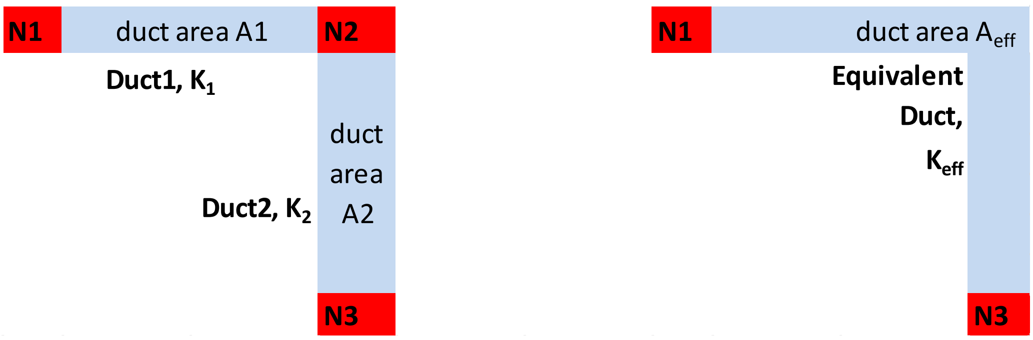


Figure 5. A representational image of a duct with three nodes and equivalent duct with two nodes.

In figure 5, left side duct has three nodes (N1, N2, N3) as shown and its loss coefficient is calculated for duct parts between each of two nodes. Right side duct is equivalent duct having same length as left duct but have different effective area as chosen and has equivalent loss coefficient as calculated by the equation (16) for two nodes N1 and N3.

II.3.3 HVAC Coupling to FDS

II.3.3.1 Boundary Conditions

Boundary Conditions for HVAC Solver

For each and every duct's node connected to the CFD domain, HVAC solver requires boundary conditions of pressure, temperature, and species. For flows from duct to CFD domain, temperature and species are taken as the density weighted average of the gas cell adjacent to the vent coupling the HVAC solver to CFD domain. Pressure is taken as the area weighted total pressure over the vent [10]. In the figure 2 the node “i” which is connected to CFD domain representing a room basically abuts the cell named “i” on which a “vent” is defined in FDS. In this gas cell above mentioned calculations are done to give boundary conditions to HVAC solver. The cell “i” in CFD domain will pass the parameters of boundary conditions to the node “i” of the HVAC as the node “i” is connected to vent patch defined over one of the face of cell “i” which is right side face in given figure 2. For more detail refer to [7].

Boundary Condition for FDS Hydrodynamic Solver

The mass flux and temperature predicted by HVAC solver for ducts are coupled to CFD domain through vents to which duct nodes are connected. Figure 2 can be referred to understand the coupling and passing of boundary conditions from one another. The cell containing the obstruction of CFD domain on which duct node is connected has temperature boundary condition as same as duct temperature for flows into CFD domain from HVAC. The boundary conditions for velocity, density, and species are coupled to one another and iterations are done to get the solution. For more detail refer to [7].

II.3.3.2 Solution Process in FDS and HVAC

As the two models are not fully coupled, the HVAC model uses the prior time step gas cell values as the boundary condition for HVAC solver. And HVAC solution will then become the boundary condition for current FDS time step. The pressure computed is an estimate of the pressure at the end of the time step based upon the pressure rise in the prior time step and it will contain some error which would not be large as pressure typically changes slowly [10].

The HVAC solution is updated in the predictor-corrector step of FDS. The sequence is as follows:

1. Boundary conditions at all points where the HVAC network joins the FDS computational domain is updated using the previous time step values.
2. The extrapolated pressures for each pressure zone is computed using the previous iteration (previous time step if the first iteration).
3. Linear set of equations for conservation of momentum and conservation of mass are assembled and solved.
4. Errors in mass conservation, flow reversal over the time step, and the magnitude of change in the velocity solution for each duct is checked. If any convergence check fails, the solution is re-iterated with new extrapolated pressures. After each iteration, the temperature and density of each node are updated using the velocity and pressure solution. The node temperature is computed by summing the enthalpy flowing into the node and computes the average temperature that represents the total enthalpy. Density is then updated using the equation of state and the new temperature [7].

II.3.3.3 Limitations of HVAC Solver

Although the solver correctly predicts the pressure drop in the duct, correctly captures the buoyancy effect and can simulate large duct networks, it has some limitation which can be dealt with future work. Some of it current limitations [10] are

1. No reaction is possible within HVAC network. In reality if hot fire gas gets in contact with fresh air in duct then fire can happen inside the duct.
2. No heat transfer can take place from ducts to surrounding while in actual case a heated duct can lose heat to its surrounding or cold duct can warm up.
3. No mass storage can happen in the HVAC network. What flows in comes out in the same time step.
4. No account for transport time of species in the duct. There is no time delay in the movement of species through the length of ducts.
5. No energy loss to duct can happen from the fluid flowing in the duct.
6. Duct construction is not visible in SMV files.

III. Case Description and Computational Set-up (Methodology)

In this section, full description about room configuration, fire parameters of the experiment, ventilation system used for the set-up, cases for validations, types of simulations and data for ventilation fan have been discussed.

III.1 Description of the test cases.

In this section, room configuration, CFD domain, fire parameters, ventilation system and cases for validation are described.

III.1.1 Room configuration and CFD domain

The geometrical configuration considered here is a tightly sealed compartment with dimensions 6 m length, 5 m width and 4 m height (figure 6). The wall of the room is made 0.1 m thick. The room is connected to ambient conditions by two ducts connected to the room. One duct is having an inlet fan and another duct is having an outlet fan. Both the ventilation ducts with cross-sectional dimensions 0.4 m x 0.4 m are positioned at height of 3.9 m on the ceiling. Area for leakage from the walls is 5 cm^2 and same value is used for ventilation validation. Leakage vents are made for simulation to allow leakages. The total computational domain is (x) 6 m, (y) 5 m, (z) 4 m.

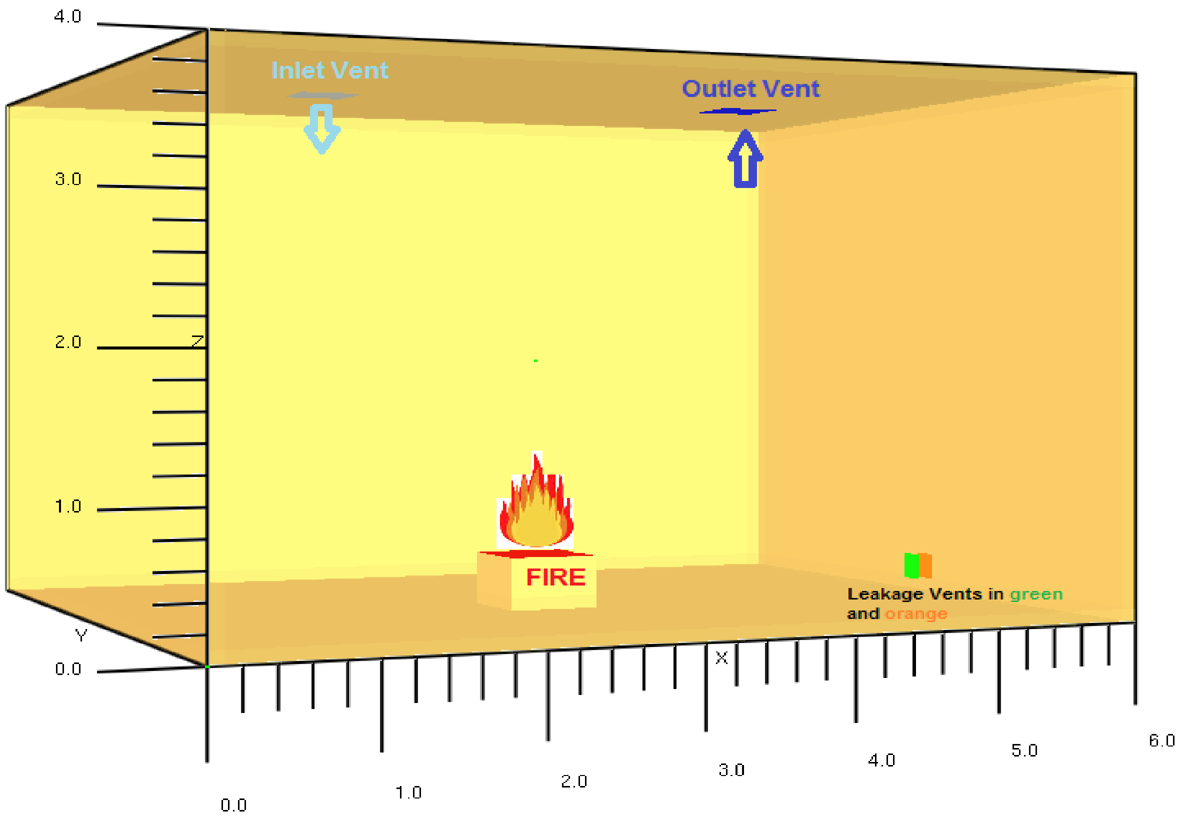


Figure 6. Geometrical configuration of the room in FDS

III.1.2 Fire Parameters

Small pool fire (0.4 m^2) of Heptane is put in the centre of the room to study its effect on the ventilation conditions. Data of mass loss rate per unit time (MLRPUA, kg/s.m^2) available from the experiment has been used for the simulations of fire in FDS. The loss of mass actually starts around 1150 s from the time of start of experiment and average mass rate is 0.0113 kg/s (MLRPUA is 0.02825 kg/s.m^2) (figure 7). Two cyclic trend of fluctuation gets completed at around 1650 seconds (500 seconds from 1150 seconds). So all the fire simulations with varying mass loss rate are done for at least 500 seconds.

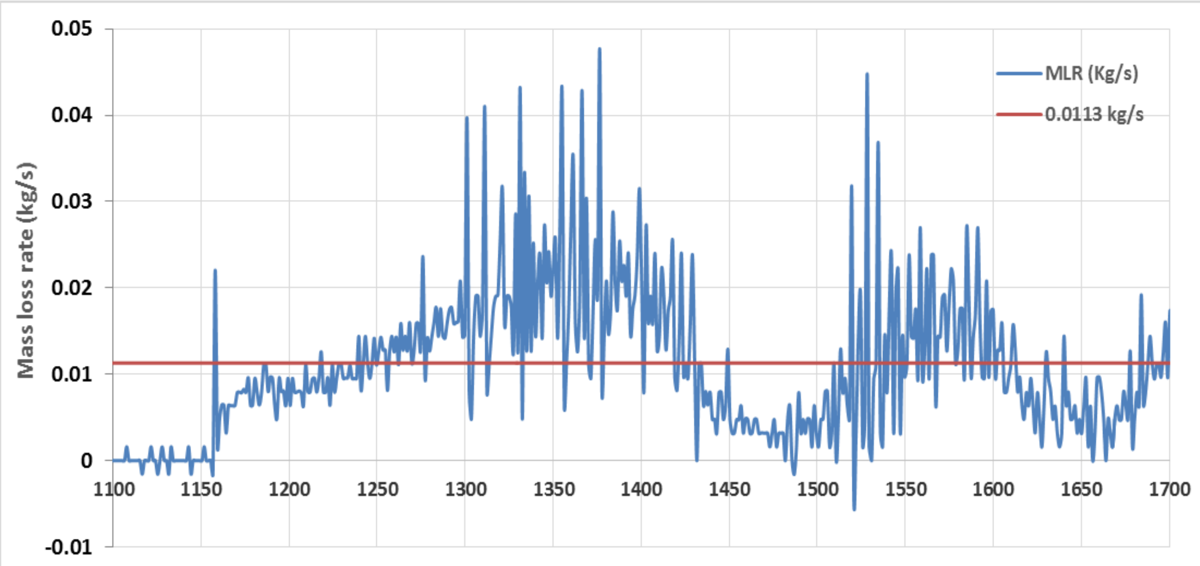
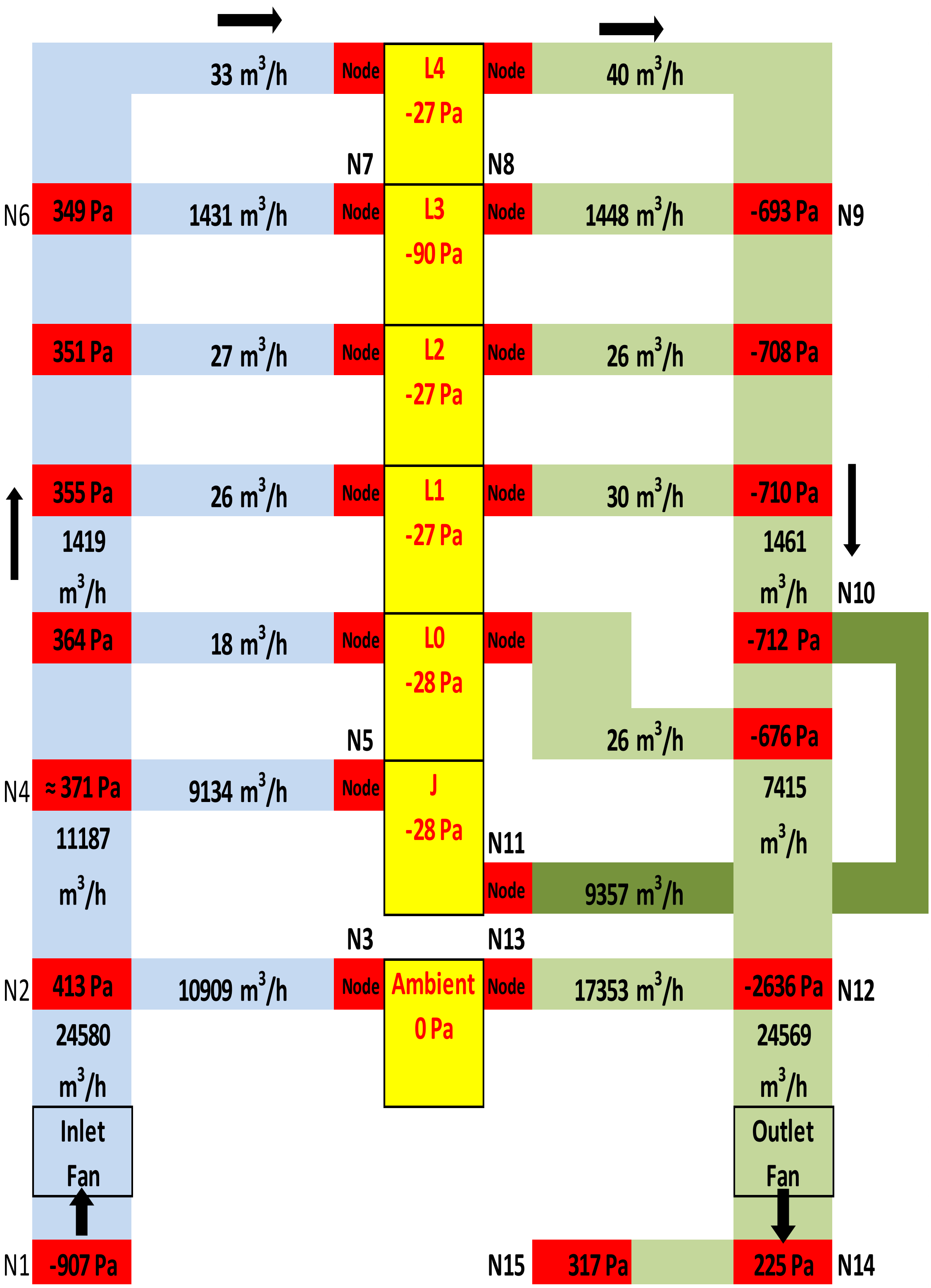


Figure 7. Mass loss rate vs time graph for 500 seconds from the start of fire with average mass loss rate value (shown by horizontal red line).

III.1.3 Ventilation System

The room (named L3) in consideration is actually connected to a complex network of ventilation which is shown in figure 8. “J” denotes a room named Jupiter.

In order to model HVAC in FDS, the volumetric flow between the two nodes with their pressure is needed to calculate the loss coefficient for the ducts. To do so the network has been modified as shown in figure 9.



XYZ m³/hr	Volumetric flow rate in ducts
Node	depicts a node with its pressure or connected to room

Figure 8. Actual Ventilation network connected to the facility (Conditions before fire).

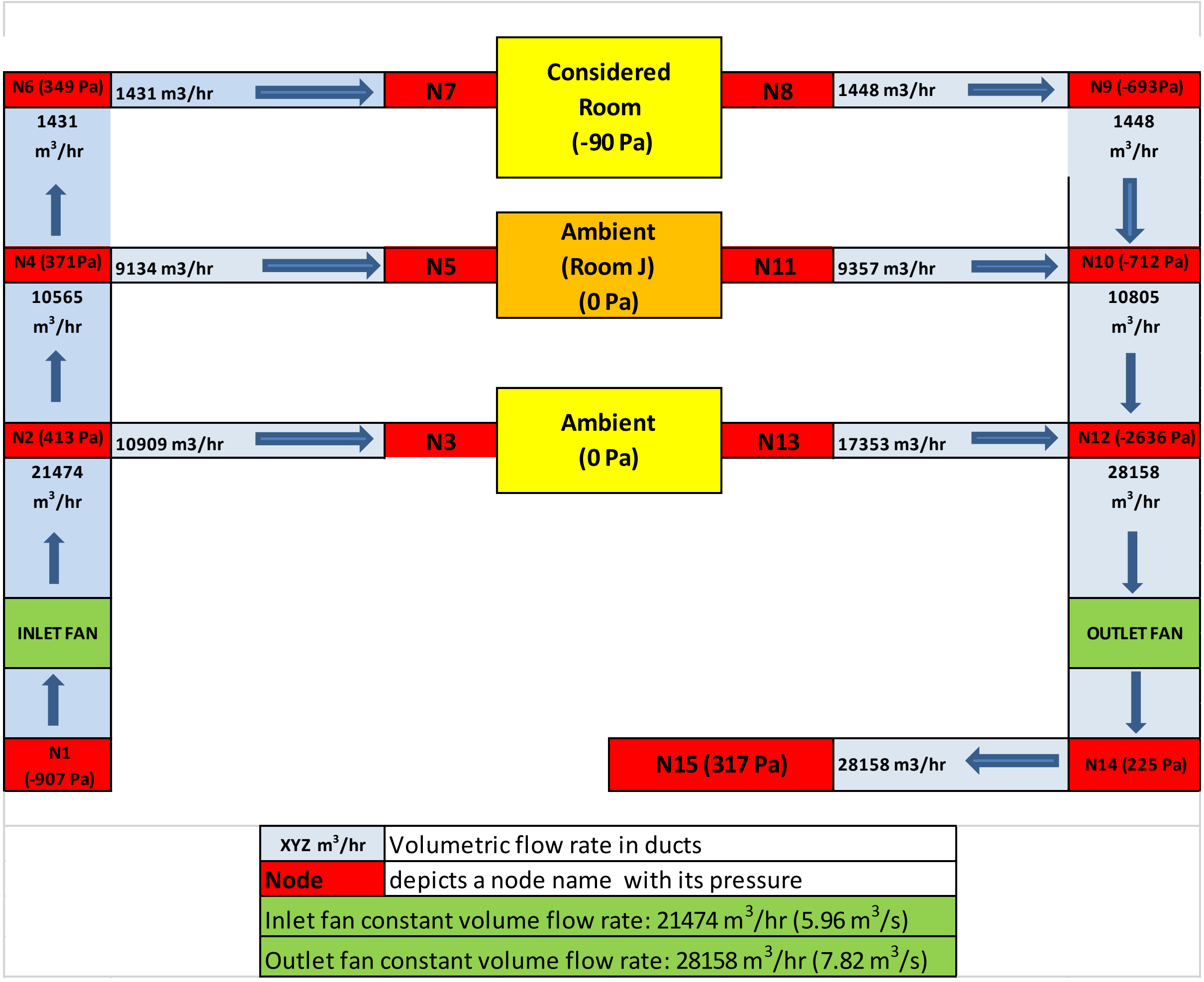


Figure 9. Modified Complex Ventilation Network connected to the facility (conditions before fire).

In the modified case (figure 9), rooms L4, L2, L1, L0 have not been considered as the ducts connected to these rooms are having total flow (sum) which is less than 0.5 % of flow in the network starting from the (inlet) fan and their exclusion does not make any significant change in the network. Moreover L3 is the room in consideration and major flow is happening into the room "J" and room depicted with ambient condition. Here, room "J" has been considered because the duct connected to it has almost 38 % of the flow starting from the fan and it is important to include such flow in the network or else the (modified) volumetric flow rate assigned to the fan will be very low in value for the network and will not approximately match the real value of volumetric flow rate of the fan designed for the network. Same reason applies for the flow into or from the ambient condition (below room J) as it also accounts for more than 44% flow in the network. Moreover, room "J" is not in the consideration and only concern about it is the flow in and out of it, so it has been assigned the ambient condition as -28 Pa pressure in the room account for almost same loss coefficient as 0 Pa. But in the case when room "J" is having significant pressure which can lead to loss coefficient value which is not same as room "J" being assigned 0 Pa then in that case the actual pressure of the room "J" has to be considered and also has to be included in the calculation of the loss coefficient.

Same reasoning also applies for the exhaust ducts and their simplification to modified ventilation network.

As volume flow for the ducts connected to these rooms (L3, J, ambient) are available, so flow in these rooms can be simplified with back flow calculation starting from node N7 and related calculation of loss coefficient using equation (15) can be done using nodal pressures.

Between node N7 and N6 the volumetric flow rate is 1431 m^3/h. This must be maintained in the duct between N6 and N4 so the flow in this duct is 1431 m^3/h assuming that there is no leakage. At node N4, total outgoing flow is 10565 m^3/h (9134 m^3/h (towards N5) + 1431 m^3/h (towards N6)). So flow between node N4 and N2 is 10565 m^3/h. Similarly adding outgoing flow at node N2 (10909 m^3/h (towards N3) + 10565 m^3/h (towards N4)), flow in the duct between node N2 and N1 amounts to 21474 m^3/h which is fixed volumetric flow rate of the fan considered in the modified case. Now as the volume flow rate in each duct with their node pressure is known, using the equation 15 the loss coefficient for each duct is calculated for FDS computation. Same approach of flow balance at each node is also done for outlet ducts.

III.1.4 Cases for Validation

Data of effect of fire on pressure variation in the room and volumetric flow rates in the ducts connected to the room L3 is available. Two different ways have been used to check the possibility of validation of fire effect on the room and ducts in FDS. In first case, an attempt has been made to check whether it is possible to have same effect on pressure variation in the room and volumetric flow rates in the ducts if the room ducts are made to be directly connected to the ambient node as shown in figure 10 and fire condition is kept same. This configuration will be referred as local network as it involves simple ventilation configuration. In second case, the effects of fire has been analyzed keeping complex ventilation network as shown in figure 9. This configuration will be referred as global network. Details about these configurations have been covered in the following sections.

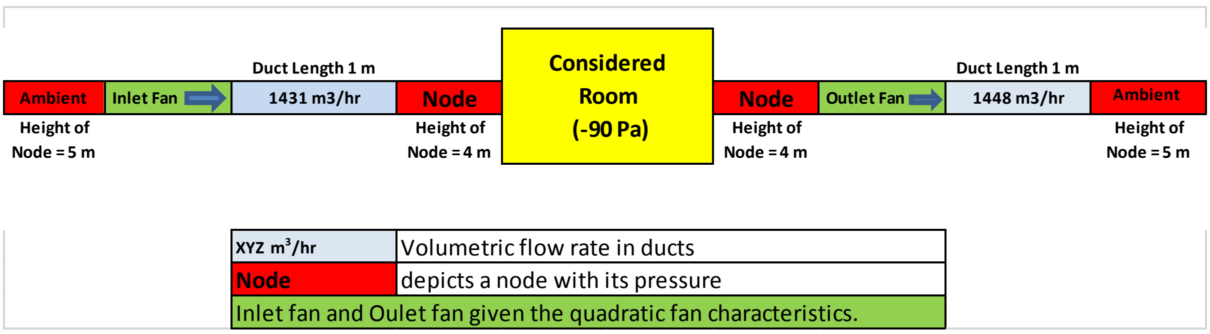


Figure 10. Local Ventilation network for the considered room.

The pressure shown in the figure 10 is an instantaneous pressure taken at some moment of time before fire. The mean pressure before fire is 86 Pa with standard deviation of 5 Pa and minimum pressure being -103 Pa and maximum is -74 Pa recorded before fire in the ventilated condition. It is expected that pressure in the room in simulation can range from -74 Pa to -103 Pa.

For both the cases, first the ventilation conditions are validated in FDS and then the effect of fire on room pressure and volumetric flow rate in the duct is checked to match the experimental data.

III.2 Descriptions of Simulations

Simulations have been categorized as non-fire simulations and fire simulations and are described in details in the proceeding sections.

III.2.1 Non Fire Simulations

Before carrying out the simulations to validate the test conditions, sensitivity studies have been done to study the effect of varying the various HVAC input requirements like duct length, roughness of duct, area of leakages and ambient node coordinates, on the pressure variation and volumetric flow rates in a well-confined and mechanically ventilated room. For this, local ventilation configuration as shown in figure 10 has been taken and loss coefficients for ducts have calculated based on this configuration. The length of the duct is taken as 1 m, and the area of leakage through wall has been chosen 0 cm^2 as base values. Galvanized steel (roughness value: 0.15 mm [14]) is most commonly used for the fabrication of ducts. As the fabrication material of the duct is not known, it is assumed to be made of galvanized steel and the roughness for the case is taken as 0.15 mm or 0.00015 m as the base value. The height of the ambient node is kept 1 m high from room node. While doing sensitivity studies, all the parameters have been varied to study their effect on the pressure created in the room and volumetric flow in the ducts.

After sensitivity study, ventilation conditions without fire have been validated for both local and global ventilation network. Parameters used in the validations are presented in the result section.

Preliminary simulations without fire were performed with cell size of 20 cm and 10 cm. No appreciable change (change was very less than 1%) was found in the results given by simulations performed by mesh of cell size 10 cm. As for example, the volumetric flow rate in inlet duct predicted by FDS for both the cell size was 0.37 m^3/s. Pressure also showed the steady value of 70.9 Pa in simulations for different mesh size as shown in figure 11. So all the simulations without fire were done with mesh of cell size 20 cm to save time.

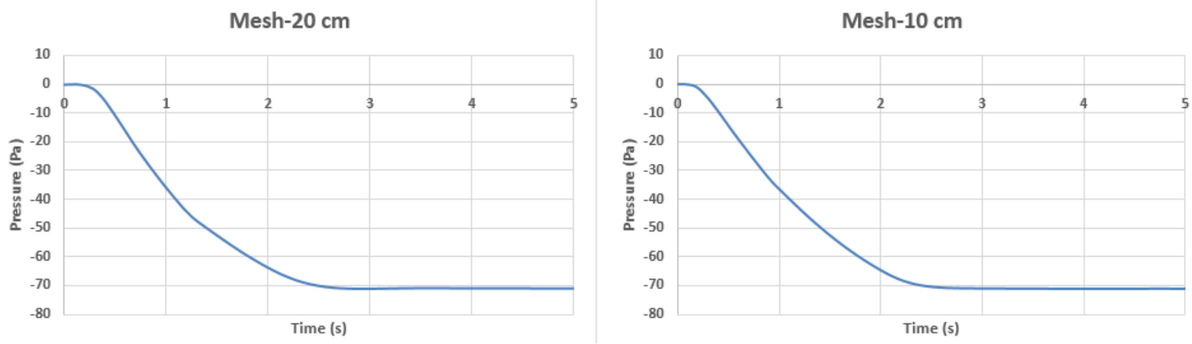


Figure 11. Graph showing the results of pressure for non-fire simulations for two different mesh size.

III.2.2 Fire Simulations

Fire has been used in the both configuration with roughness value of ducts 0.00015 m and area of leakage through walls 5 cm^2. Heptane is used as a fuel and a small pool fire with area 0.4 m^2 is created in the center of the room. The soot value has been taken as 0.015 [15]. 27 kg of Heptane has been burnt in the room and its mass variation with time has been provided. From the mass variation data with respect to time mass loss rate has been calculated. The values of mass loss rate has been ramped in FDS to have the actual effect of mass loss rate in the simulation for both local and global ventilation network conditions. As the mass loss rate fluctuates with time because of conditions in the room getting ventilated and under ventilated over the course of fire, its effect on the pressure in the room and flow in the duct is studied through the results of simulations.

Quadratic characteristics have been assigned to the fan in simulations for local ventilation case. In case of global ventilation network, as it is not possible to get the quadratic characteristics of the fan from the available data so here the fan has been assigned fixed volume flow rate as shown in figure 9 and mass loss rate per unit area has also been ramped to see the pressure and volumetric flow fluctuation in simulation.

Another case has also been considered in which the average mass loss rate (constant value) during fire in the experiment is used in the simulation. This is done for both local and global ventilation network configuration to compare their results with each other and their results in the case of varying mass loss rate.

As the results of simulations are mesh sensitive, using the equation (6) $D^*/\delta x$ has been calculated to find the optimum mesh size to get the reliable result. Here the heat release rate Q has been taken as 462 kW which is the average value of fluctuating heat release rate in the room. The value for ρ is 1.204 kg/m^3, C_p is 1.005 kJ/kg-K, and T is 293 K. Preliminary simulations were done with coarse mesh (30, 25, 20) (D*/δx ≈4), intermediate mesh (60, 50, 40) and refined towards moderate mesh (90, 72, 60) (D*/δx ≈10), to check any appreciable change in the results. It was found that there is no significant change in the pressure profile or volumetric flow rate profile when mesh was refined from intermediate to moderate mesh. So all the simulations results involving fire have been taken from moderate mesh simulations taking into account the time constraint also. For example, figure 12 shows the volumetric flow rates for a fire simulation with constant MLRPUA for intermediate and moderate mesh. It can be noted from the graph (figure 12) that the average of the steady flow for both mesh is around 0.3 m^3/s and -0.5 m^3/s for inlet and outlet volumetric flow rates in the ducts respectively. Negative value for the outflow in the simulation is as per the sign convention used in the code.

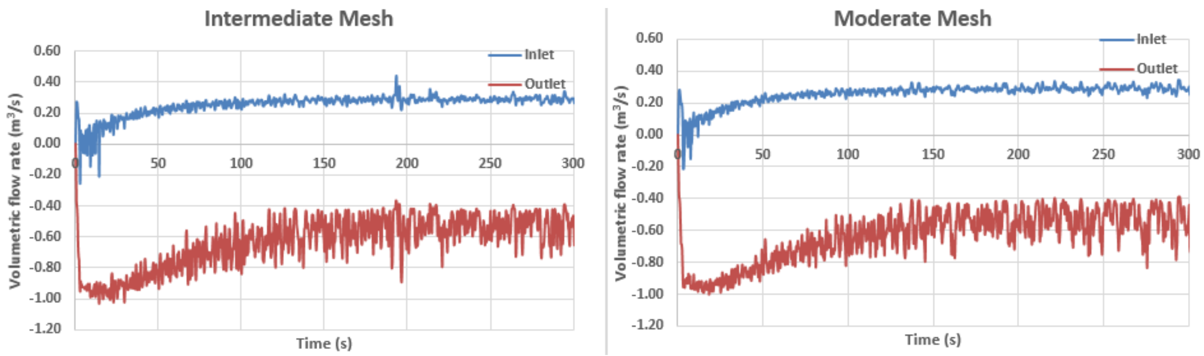


Figure 12. Graph showing the results of volumetric flow rates in ducts for fire simulations for two different mesh size (constant MLRPUA).

III.3 Data for ventilation fan

In all the simulations with and without fire for local ventilation network, the values for the stall pressure of the fan, and the volumetric flow rate of the fan at which the static pressure is zero is taken from the experimental data involving fire in the considered room.

Actual experimental data have been analyzed for the room (with same configuration) where fire was put to find the variation of the pressure in the room against the volumetric flow rate in the duct connected to the room "L3".

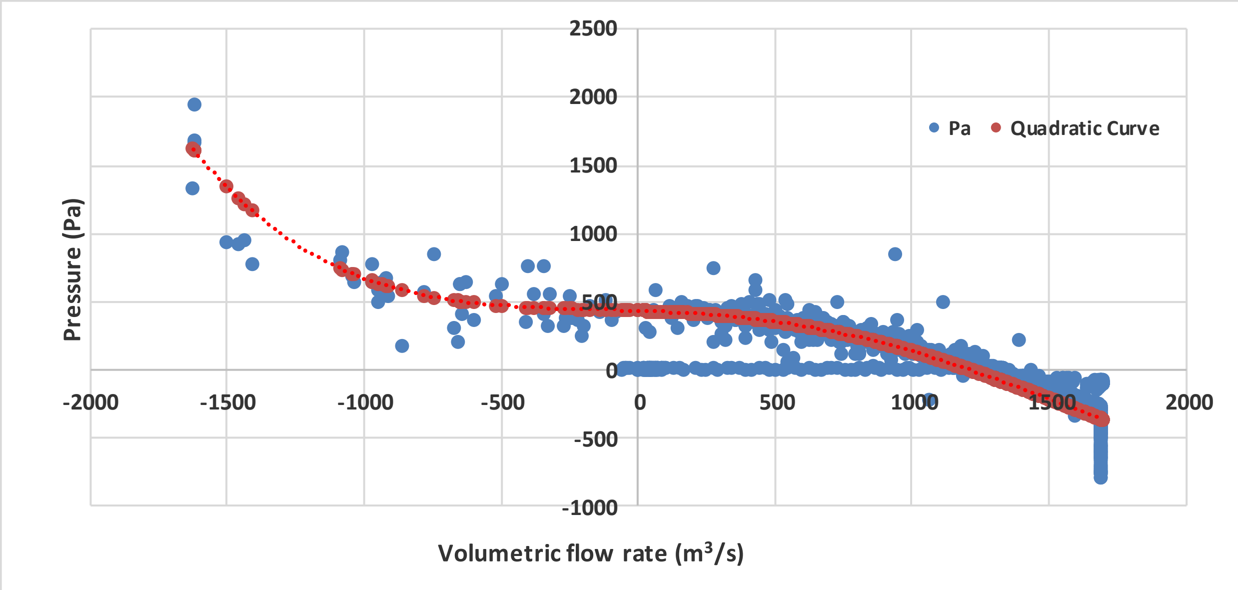


Figure 13. Pressure vs volumetric flow rate graph for inlet duct during experiment.

The blue dots in figure 13 represent the test data. The red curve has been found as the best fit among the data to represent a quadratic trend for the inlet fan.

Volumetric flow rate in the inlet duct against time and pressure in the room with respect to time was provided in the excel sheet. The graph of pressure vs volumetric flow rate was created to analyze it and to spot a quadratic trend in it. As it can be seen, the red curve fairly represents quadratic curve of the fan among the scattered data. The curve intersects the pressure axis at P= 440 Pa and intersects the volumetric flow rate axis at 1240 m^3/h (0.3444 m^3/s). In FDS, P = 440 Pa is used as stall pressure and V = 0. 3444m^3/s will be considered as flow in the inlet duct when pressure is zero.

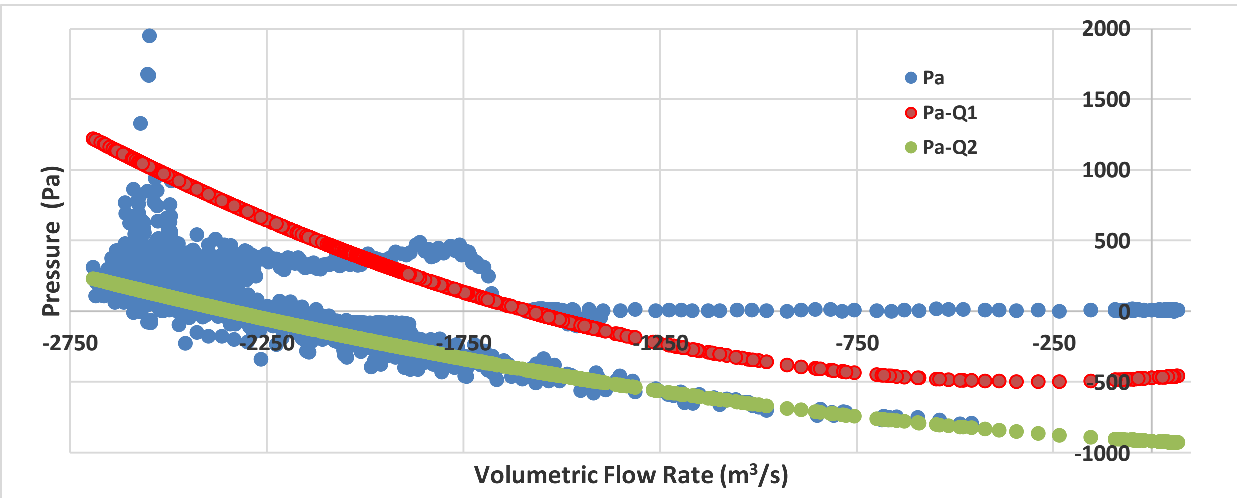


Figure 14. Pressure vs volumetric flow rate graph for outlet duct during experiment.

The blue dots represent the test data (figure 14). The red curve Q1 and green curve Q2 have been found as the best fit among the data to represent a quadratic trend for the outlet fan. The two curves are further analyzed to accept only the one between them.

Volumetric flow rate in the outlet duct against time and pressure in the room with respect to time was also provided in the excel sheet. The graph of pressure vs volumetric flow rate was created to analyze it and to spot a quadratic trend in it. As it can be seen in figure 14, the orange curve and grey curve fairly represent quadratic curve of the fan among the scattered data. The orange curve intersects the pressure axis at P= -472 Pa and intersects the volumetric flow rate axis at -1580 m^3/h (-0.4388 m^3/s). The grey curve intersects the pressure axis at P= -905 Pa and intersects the volumetric flow rate axis at -2400 m^3/s. After conducting initial trial simulations, grey curve was discarded as its volumetric flow rate of -2400 m^3/s produced unreasonably very low pressure in the room (in simulations). In FDS, P = -472 Pa is used as stall pressure and V = 0. 4388 m^3/s will be considered as flow in the outlet duct when pressure is zero.

IV. Results

This section contains the results of all non-fire simulations including sensitivities studies and fire simulations.

IV.1 Non-Fire Simulations

In this section, sensitivity study along with validation of ventilation network before fire has been done for local and global ventilation network.

IV.1.1 Sensitivity Study

In the sensitivity study, fans have been allotted the quadratic characteristics as obtained from the data analysis done in the section III.2.3. Inlet fan has been given stall pressure value as 440 Pa and volumetric flow rate 1240 m^3/h. Outlet fan has been given stall pressure value as 472 Pa and volumetric flow rate 1580 m^3/h. Parameters have been varied case to case in the sensitivity studies.

IV.1.1.1 Variation of length of duct with fixed value of roughness

The parameters included in this sensitivity study are mentioned in the table 1.

Parameters	**Remark**
Length of Ducts	Varied as L=1 m, 25 m, 50 m, 75 m
Roughness of Ducts (m)	0.00015
Area of Leakage (m^2)	0
Ambient Node Z axis Coordinate	5 m

Table 1. Parameters for sensitivity study of duct length.

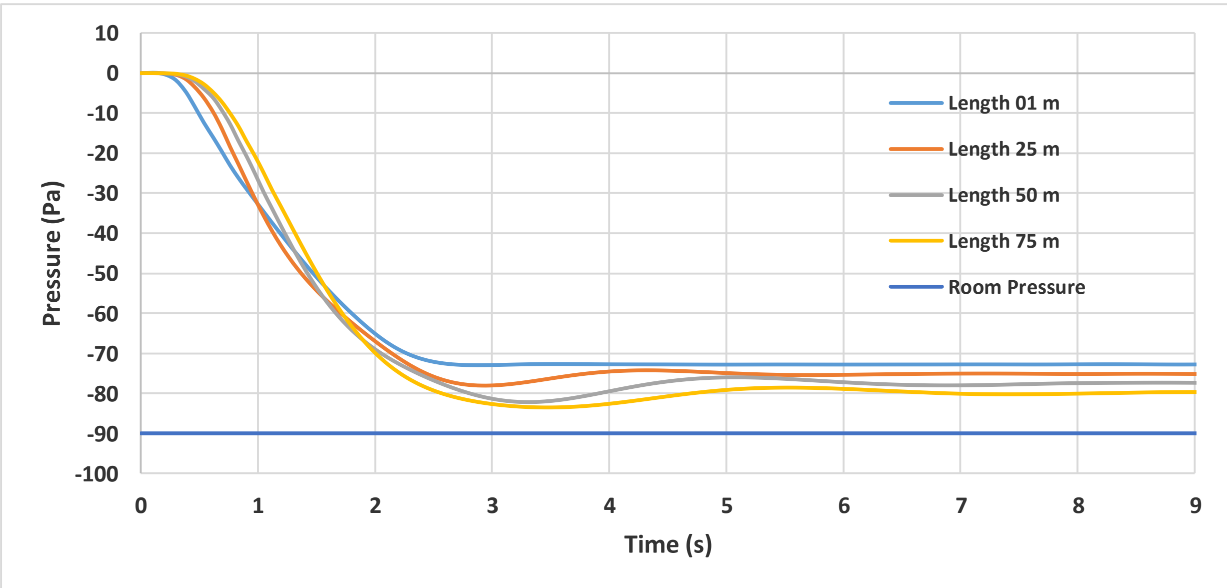


Figure 15. Pressure vs time graph for sensitivity study of duct length with fixed value of roughness

It can be noted from the figure 15 that the longer duct leads to more magnitude of negative pressure in the room and negative pressure created in the room increases with length in the given case.

From the formula $P = \rho . L \left(\frac{du}{dt}\right)$ (Newton's Second Law), (17)

where P is the pressure in pascal of the fluid of density ρ kg/m^3 contained in a volume of length L m and moving with the speed u m/s with respect to time t s, it can be noted that magnitude of the pressure created by a given volume of fluid is directly proportional to the length of the volume in which it is flowing. In the given case, pressure created in the room is the result of fluid flow in the duct's volume whose magnitude clearly increases when the duct length increases.

It can be also noted from the graph as the longer duct produces higher magnitude of negative pressure in the room, so more time is taken to reach the steady pressure for longer ducts. For example, the duct with 1 m length causes steady pressure (less in magnitude) in the room at around 2.5 s but 75 m duct causes steady pressure (more in magnitude) in the room in 7 s.

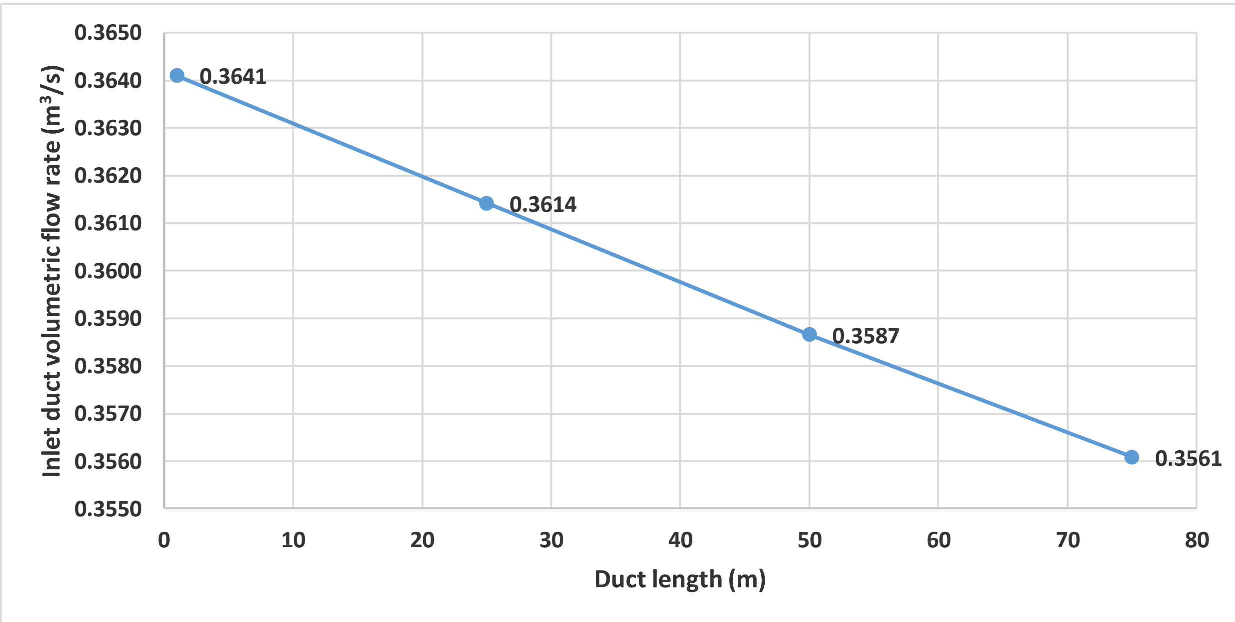


Figure 16. Inlet volumetric flow rate vs time graph for sensitivity study of duct length.

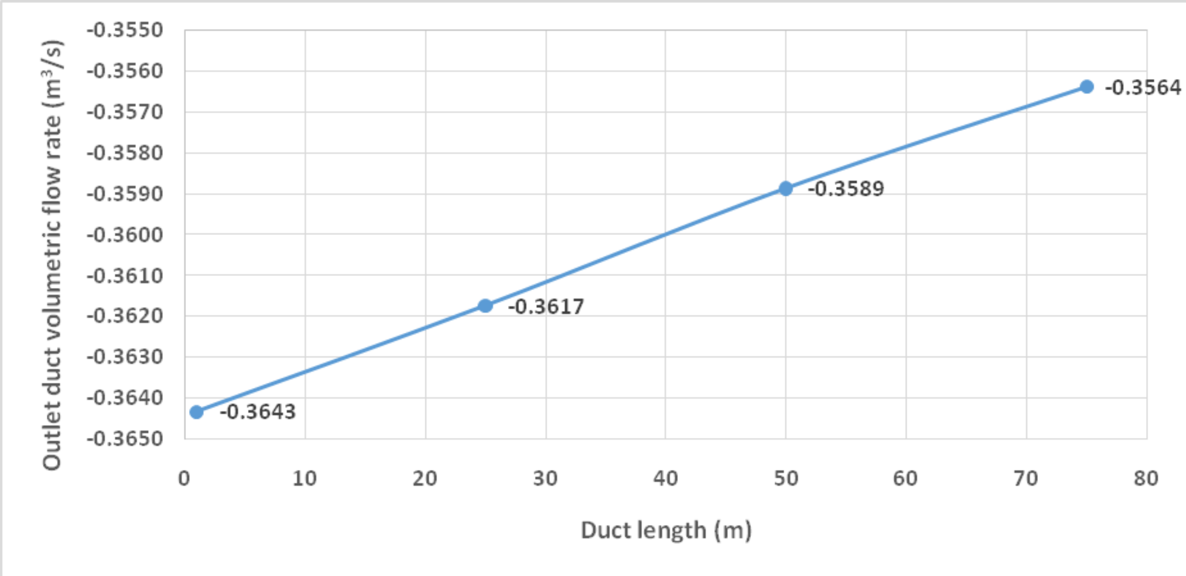


Figure 17. Outlet volumetric flow rate vs time graph for sensitivity study of duct length.

From figure 16 and figure 17 it can be noted that as the length of the duct is increased the magnitude of volumetric flow rate decreases by less than 1 % both for inlet and outlet duct. As the length of the duct is increased, the roughness (value being constant) acts for greater length causing minor pressure loss resulting in minor decrease in the volumetric flow rate. It should be noted here that overall pressure as stated in equation 17 directly increases with increase in the length of the duct due to more volume of moving fluid and minor pressure loss due to roughness does not affect much the overall pressure created in the room by the fluid in the duct. This case is prominent when the density of the fluid is low like air which is around 1.225 kg/m^3.

As the data for length of ducts are not available, all fire and non-fire simulations are done with duct length 1 m as the shortest distance between two nodes is expected to be 1 m. This 1 m duct can be the duct connecting the room vent to the first immediate node at the height of 1 m straight above it. Refer figure 10.

IV.1.1.2 Variation of length of duct with roughness value zero

The parameters included in this sensitivity study are mentioned in the table 2.

Parameters	**Remark**
Length of Ducts	L = 1 m, 25 m, 50 m
Roughness of Ducts (m)	0
Area of Leakage (m^2)	0
Ambient Node Z axis Coordinate	5 m

Table 2. Parameters for sensitivity study of duct length of with roughness value zero.

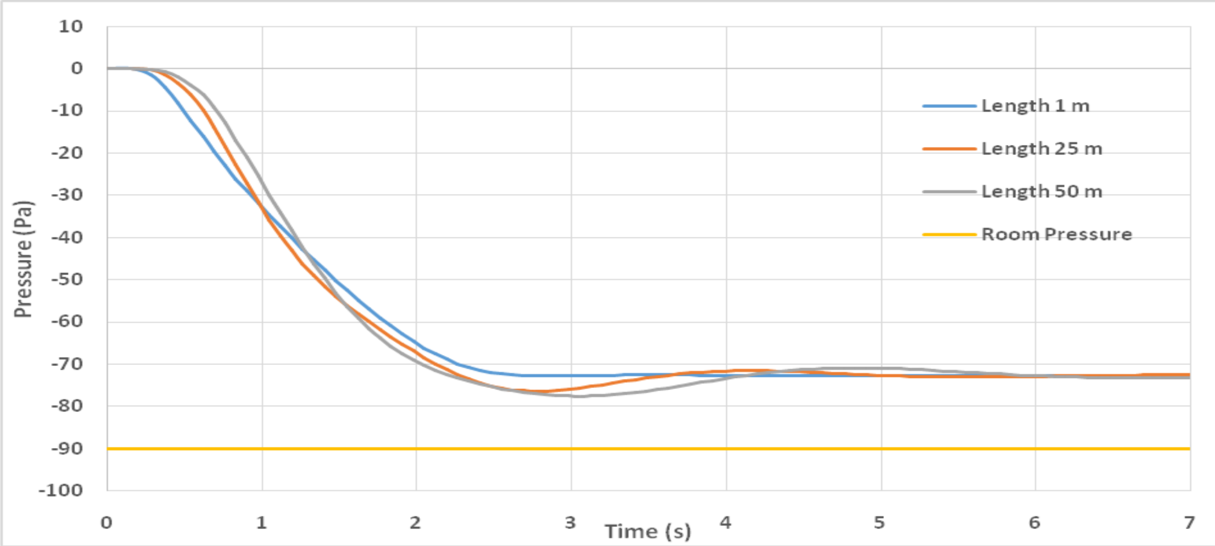


Figure 18. Pressure vs time graph for sensitivity study of duct length with roughness value zero.

On comparison of figure 18 with figure 15, it can be noted that when roughness is assigned zero value then irrespective of length of a duct, the steady pressure in the room converges at same value which is around -73 Pa in the given case. The overall loss coefficient in a duct is dependent on loss due to wall friction and loss due to fittings. When absolute roughness is put zero then loss due to wall friction gets reduced in the magnitude and is then only affected by the Reynolds number. Then loss due to fittings is mainly responsible for the loss of pressure in the pipe. The loss due to fittings remains same if fittings are not altered for different lengths of the ducts. So irrespective of the duct length, pressure generated by ducts of different lengths converge at around same value for roughness being zero and fittings not being altered.

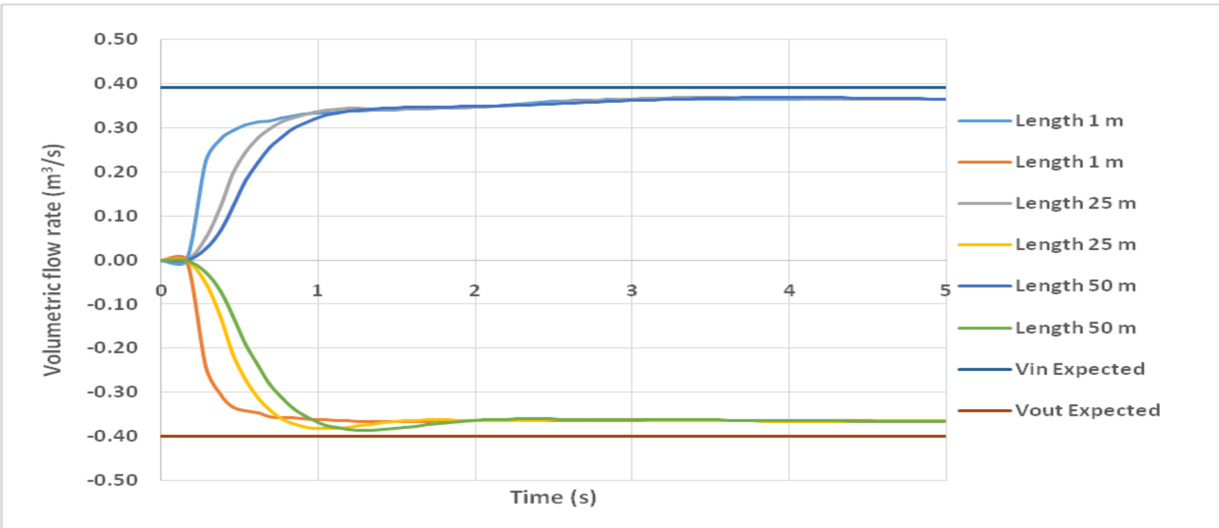


Figure 19. Volumetric flow rate vs time graph for sensitivity study of duct length with roughness value zero.

As explained before for figure 18, pressure loss in the duct remains same when roughness is zero. So due to same pressure loss, the volumetric flow does not change in the different length of ducts (figure 19) and remains 0.364 m^3/s for inlet duct and - 0.364 m^3/s for outlet duct.

IV.1.1.3 Variation of roughness with fixed value of length of duct

The parameters included in this sensitivity study are mentioned in table 3.

Parameters	**Remark**
Length of Ducts	L = 1 m
Roughness of Ducts (m)	Varied as 0.0000015 (Stainless Steel) , 0.00015 (Galvanised Steel), 0.004 (Rusted Steel) [14]
Area of Leakage (m^2)	0
Ambient Node Z axis Coordinate	5 m

Table 3. Parameters for sensitivity study of roughness.

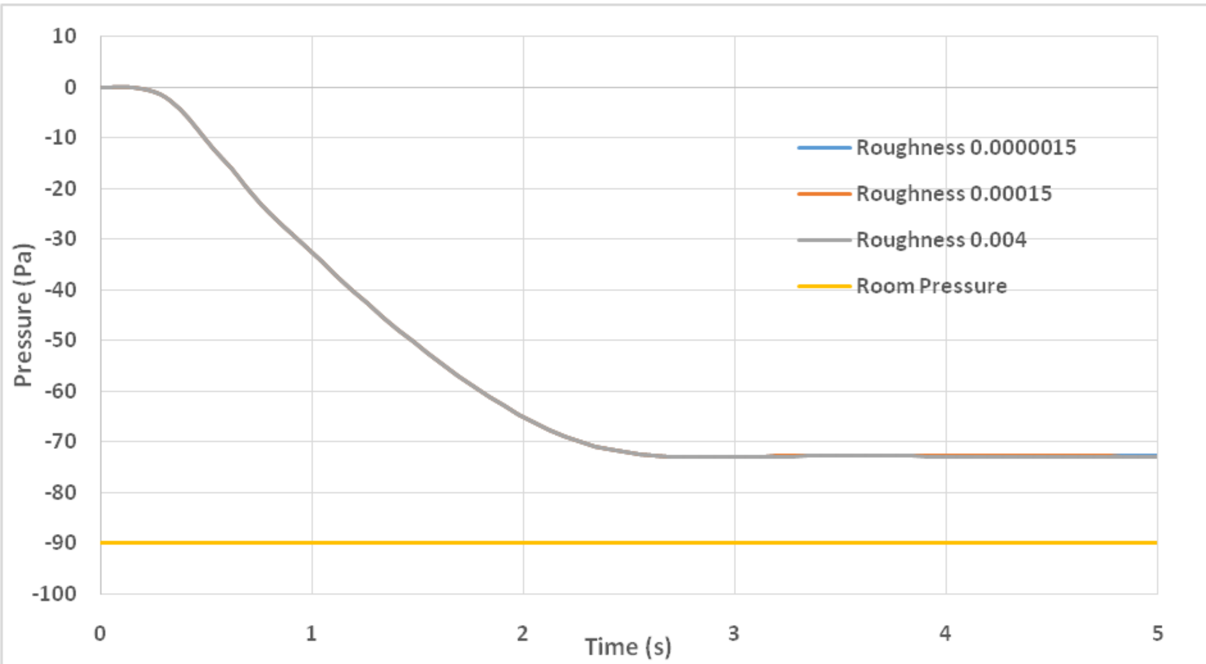


Figure 20. Pressure vs time graph for sensitivity study of roughness.

It can be noted from figure 20 that the steady pressure in the room does not change and converge at -72.7 Pa for all values of roughness for the duct. Although roughness has direct effect on the friction coefficient which in turn causes pressure loss but the density of the fluid also plays a major role. In case of air or hot gas the effect of various values of roughness is very low but in case of fluid like water whose density is almost 1000 times the air the effect of increasing the roughness is significant.

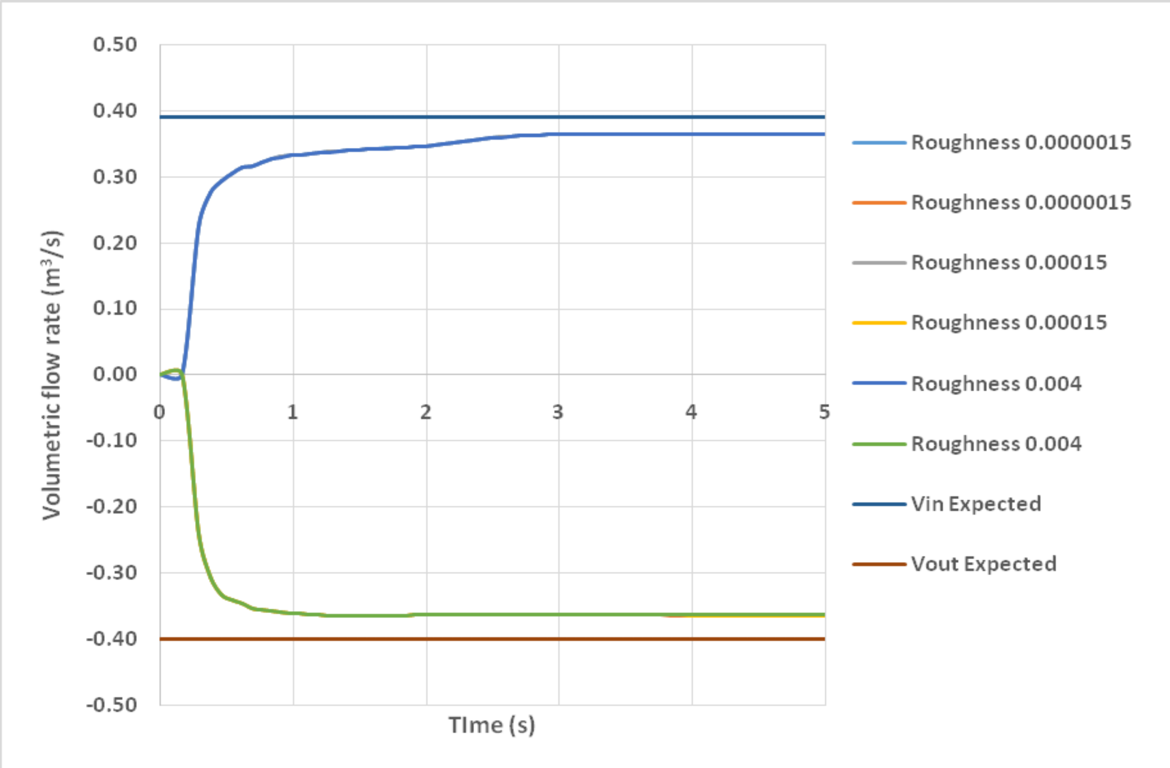


Figure 21. Volumetric flow rate vs time graph for sensitivity study of roughness.

As the density of air is low there is no difference is seen (figure 21) in the volumetric flow rates in both inlet and outlet duct for various values of roughness. The volumetric flow rate in steady state remains at 0.36 m^3/s for inlet duct and at -0.36 m^3/s for outlet duct for all values of roughness.

IV.1.1.4 Variation of area of leakage

The parameters included in this sensitivity study are mentioned in table 4.

Parameters	**Remark**
Length of Ducts	L = 1 m
Roughness of Ducts (m)	0.00015
Area of Leakage (m^2)	0, 0.0005, 0.001, 0.002
Ambient Node Z axis Coordinate	5 m

Table 4. Parameters for sensitivity study of area of leakages.

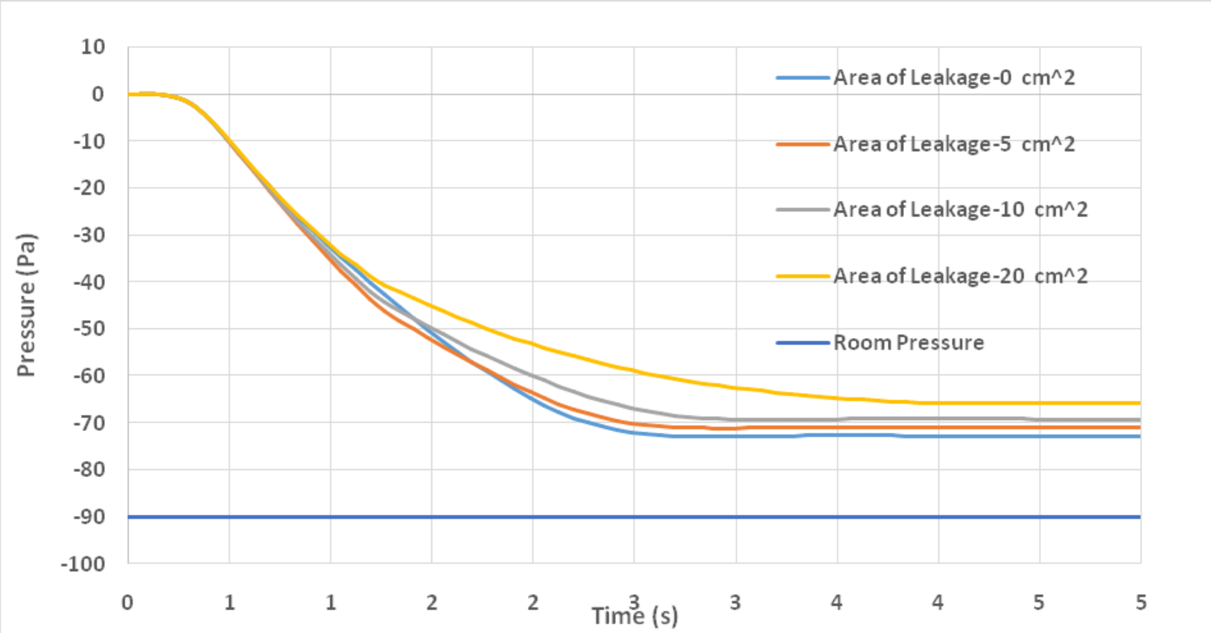


Figure 22. Pressure vs time graph for sensitivity study of area of leakages.

The relative ambient pressure is 0 pascal. As the area of leakage increases the pressure (relative pressure) in the room starts to decrease. This is due to the fact that pressure difference in compartment from ambient is inversely proportional to the area of leakage to the ambient condition (in the given case). So as the area of leakage increases the pressure in the compartment tends to approach the ambient pressure value (0 Pa). It can be noted from the figure 22 that when area of leakage is 0 cm^2 then pressure in the room is -71 Pa. When area of leakage is made 20 cm^2 then pressure in the room is -66 Pa.

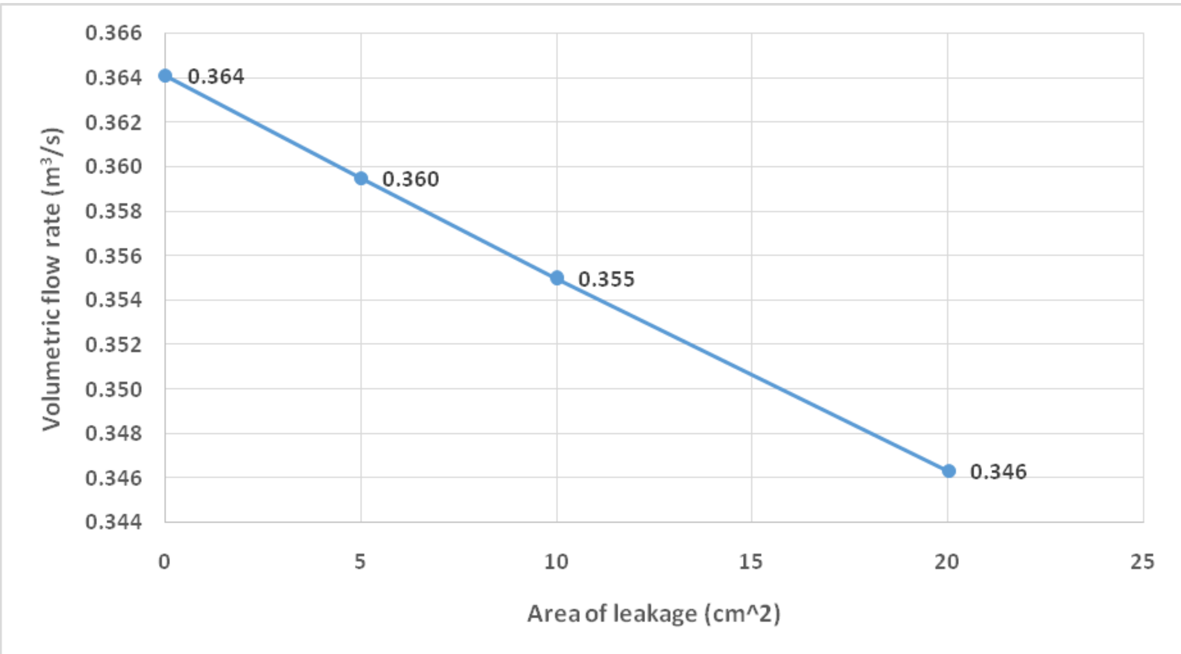


Figure 23. Inlet volumetric flow rate vs time graph for sensitivity study of area of leakage.

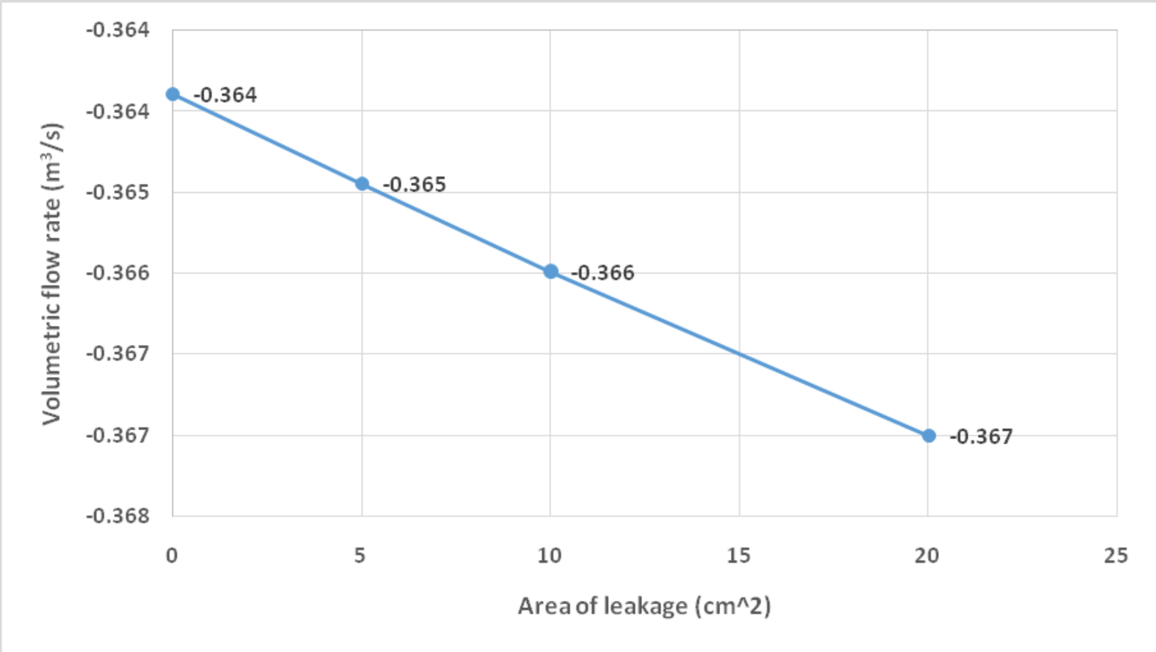


Figure 24. Outlet volumetric flow rate vs time graph for sensitivity study of area of leakage.

As pressure in the room gets less negative with increase in the area of the leakage, the magnitude of increase in pressure causes reduction in the inlet volumetric flow rate (figure 23) and increment in the outlet volumetric flow rate (figure 24). The quadratic behavior of fan causes change in the volume flow as pressure changes in the room.

IV.1.1.5 Variation of ambient node height.

The parameters included in this sensitivity study are mentioned in table 5.

Parameters	Remark
Length of Ducts	L = 1 m
Roughness of Ducts (m)	0.00015
Area of Leakage (m^2)	0
Ambient Node Z axis Coordinate	0, 3.9, 5, 10, 20 (m)

Table 5. Parameters for sensitivity study of ambient node height.

The inlet vent and outlet vent in the room is at height 3.9 m. With the choice of ambient node at z =0, 3.9, 5, 10 and 20 in this sensitivity study the aim was to make reasonable choice for ambient node in the proceeding fire and non-fire simulations.

Z-coordinate (Ambient node height in m)	Pressure (Pa)
0	-72.73
3.9	-72.76
5	-72.77
10	-72.82
20	-73.01

Table 6. Ambient node height (m) and corresponding pressure (Pa) obtained in simulations.

For the given data used in the sensitivity study it can be noted from the table 6 that with the variation of ambient node height from 0 m to 20 m, the pressure in the room has changed by 0.384 %. Moreover the volumetric flow rate in the inlet and outlet duct also remains same as 0.36 m^3/s and -0.36 m^3/s respectively for such range of node height variation. As same range of data will be used in fire and non-fire simulations and ambient co-ordinate is not known, Z= 5 has been chosen as ambient node z-axis coordinate for all simulations to validate the experimental data.

IV.1.2 Simulation and validation of local ventilation network

Parameters used in this simulation are shown in table 7.

Fan Parameters	Fan (Inlet)	Fan (Outlet)
MAX_Flow (m^3/s)	0.3444	0.4388
MAX_PRESSURE (Pa)	440	472
Other Parameters	**Values**	
Roughness of Ducts	0.00015 m	
Cross Sectional Area of Ducts	0.16 m^2	
Area of Leakage	5 cm^2	
Length of each ducts	1 m	
Loss coefficients of each duct	as shown in figure 25	

Table 7. Parameters for simulation of local ventilation network.

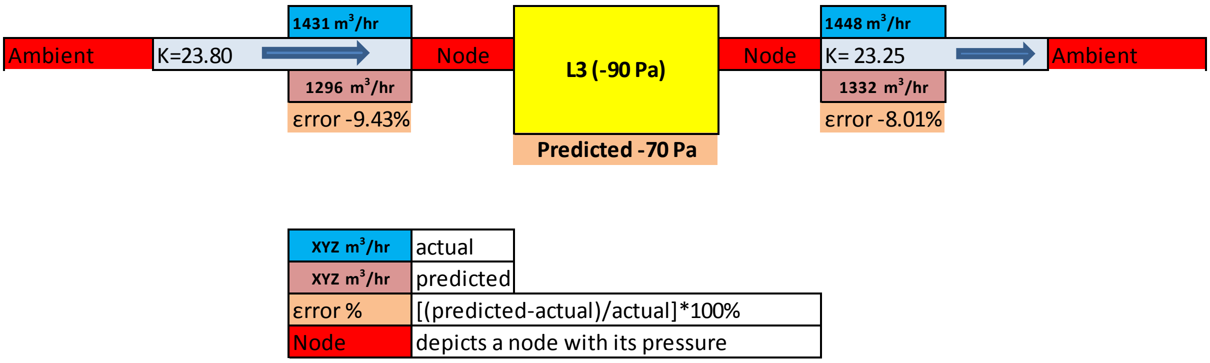


Figure 25. Validation result of local ventilation network.

It can be noted from the figure 25 that FDS is able to predict the volumetric flow rate in ducts with errors less than 10% and steady pressure prediction is -70 Pa which is close to maximum pressure which is -74 Pa recorded before fire in the ventilated condition (refer section III.1.4). There can be multiple reasons for the under prediction of pressure and volumetric flow rates in the ducts. There can be error in the chosen parameters for the quadratic fan curve or length of the duct or cross sectional area of the duct. With actual data for various input parameters the prediction is hoped to be done with less errors. This validated network is used for fire simulation for local ventilation network.

IV.1.3 Simulation and validation of global ventilation network

Parameters used in this simulation are shown in table 8.

Parameters	**Fan (Inlet)**	**Fan (Outlet)**
Volume_Flow (m^3/s)	5.96	7.82
Parameters	**Values**	
Roughness of Ducts	0.00015 m	
Cross Sectional Area of Ducts	0.16 m^2	
Area of Leakage	5 cm^2	
Length of each ducts	1 m	
Loss coefficients of each duct	as shown in figure 26	

Table 8. Parameters for simulation of global ventilation network.

Result of the simulation is shown in figure 26.

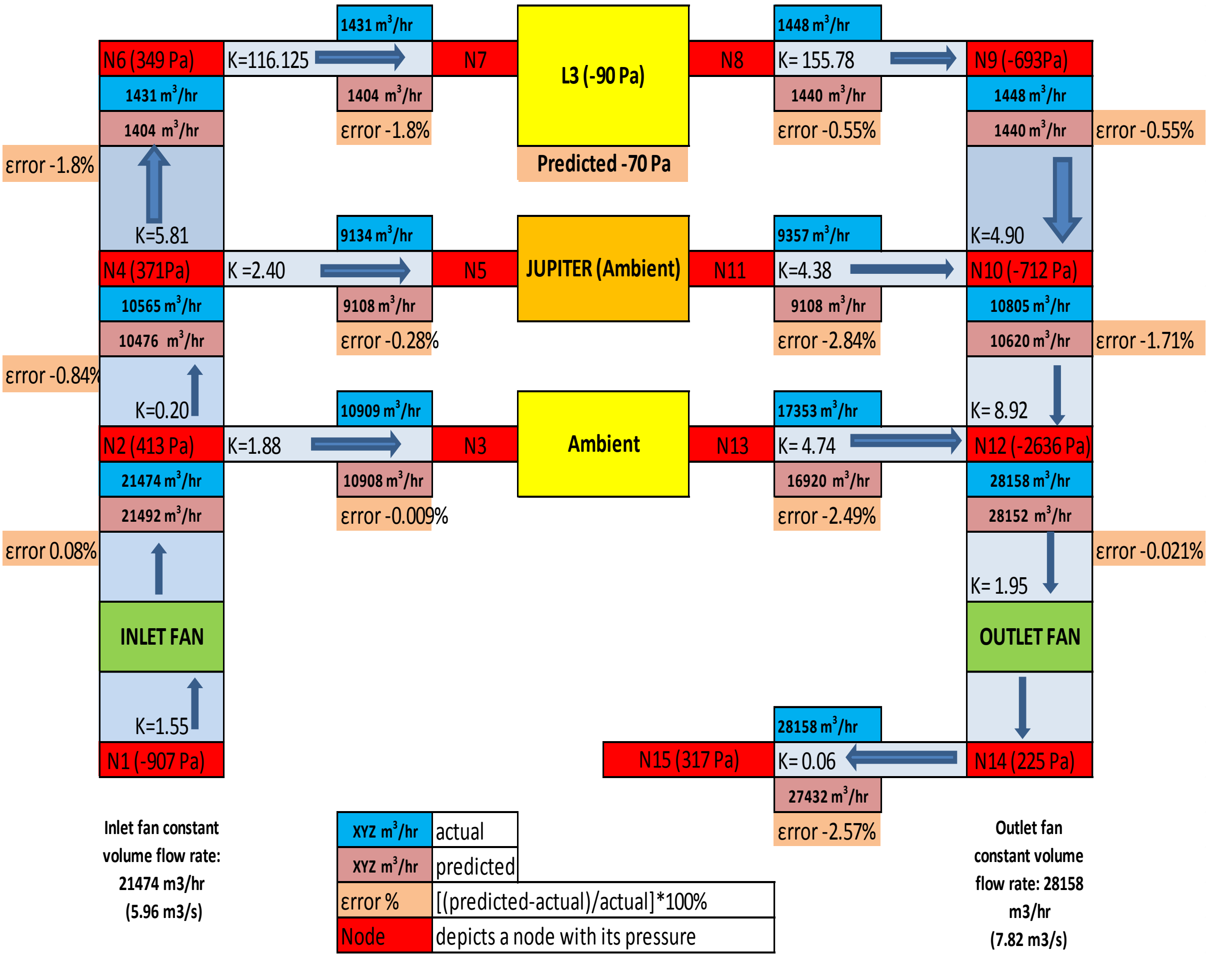


Figure 26. Global ventilation network validation flow chart for non-fire simulation and steady state.

It can noted from the figure 26 that FDS (with the modified volumetric flow rate mentioned in figure 9) is able to predict the volumetric flow rate in various ducts with errors less than 3 %. The loss coefficient (K) for each duct is individually calculated taking into account the node pressure using the equation 15. This validated network is used in the fire simulation for global ventilation network.

IV.2 Fire Simulations

IV.2.1 Local Ventilation Network Simulation with ramped MLRPUA

The validated local ventilation network as shown in figure 25 has been used for fire simulation in which mass loss rate per unit area obtained from the experimental data has been ramped in FDS to see its effect on the pressure and volumetric flow rates in the ducts.

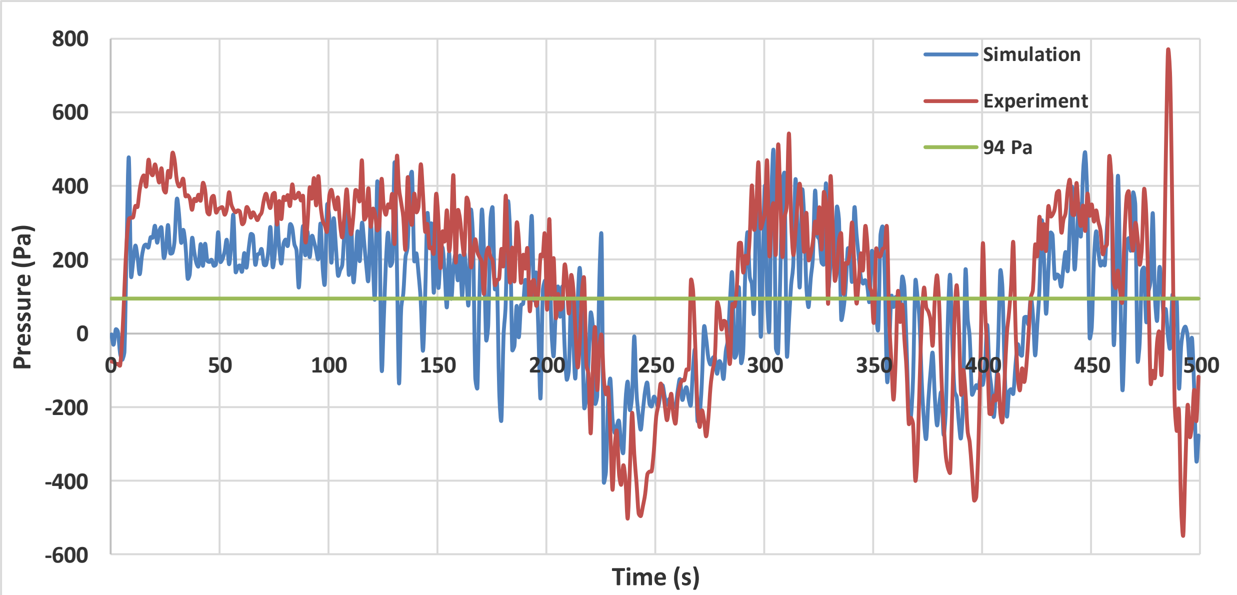


Figure 27. Pressure vs time graph of experimental data and simulation for local ventilation network (Varying MLRPUA).

As it can noted from the figure 27 that with the given input FDS has been successfully able to capture the pressure fluctuation trend with respect to the experimental data.

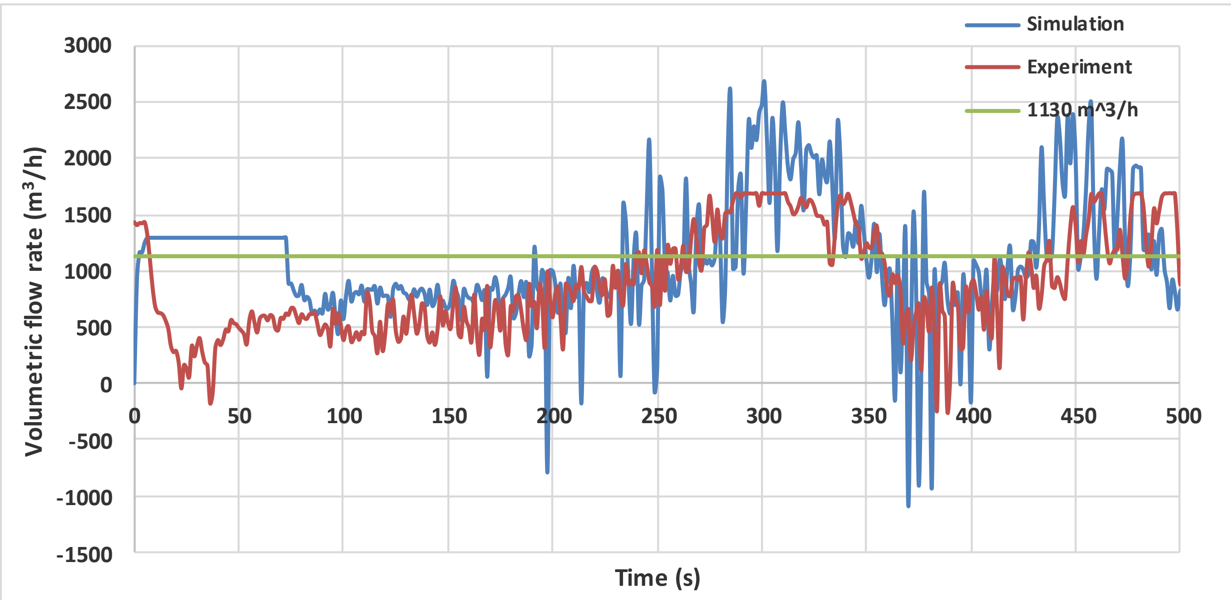


Figure 28. Volumetric flow rate vs time graph of simulation and experiment for inlet duct for local ventilation network (Varying MLRPUA).

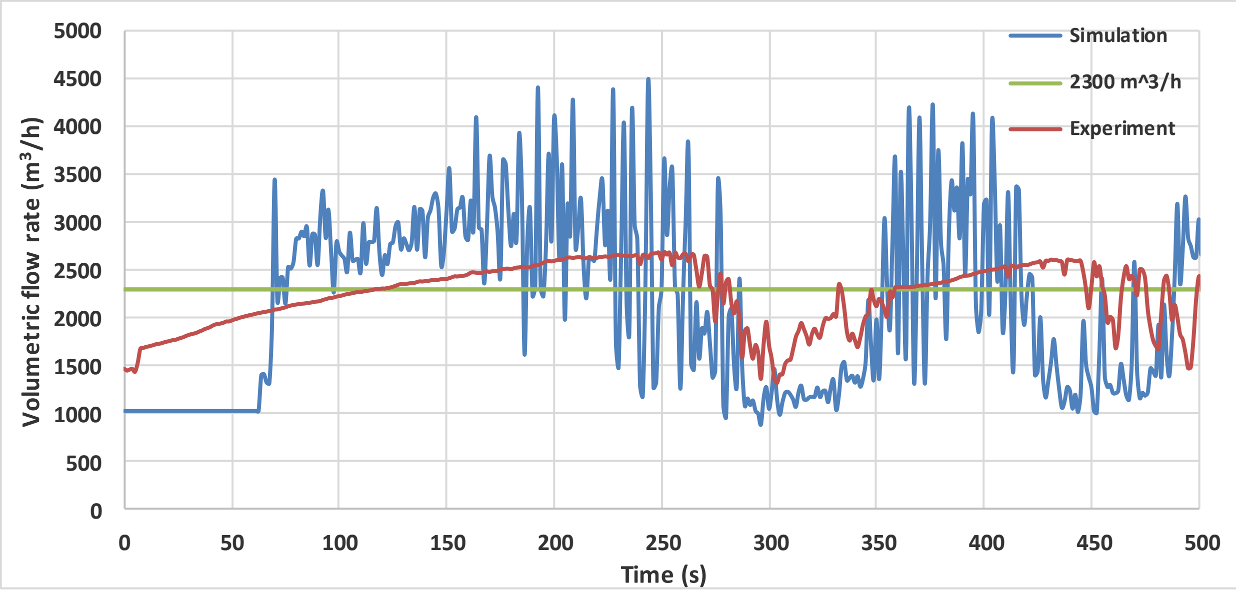


Figure 29. Volumetric flow rate vs time graph of simulation and experiment for outlet duct for local ventilation network (Varying MLRPUA).

It can noted from the figure 28 and figure 29 that with the given input FDS has been able to follow the volumetric flow rate trend with respect to the experimental data for inlet duct but not for outlet duct. As it satisfactorily replicate the inlet duct trend for the volumetric flow, there can be the possibility of error in the measurement of volumetric flow rate of outlet duct during experiment which might have led to the digression in the comparison with FDS result for outlet duct.

IV.2.2 Local Ventilation Network Simulation with fixed MLRPUA

In this case the average value of mass loss rate per unit area (0.02825 kg/s.m^2) has been used for fire in the simulation.

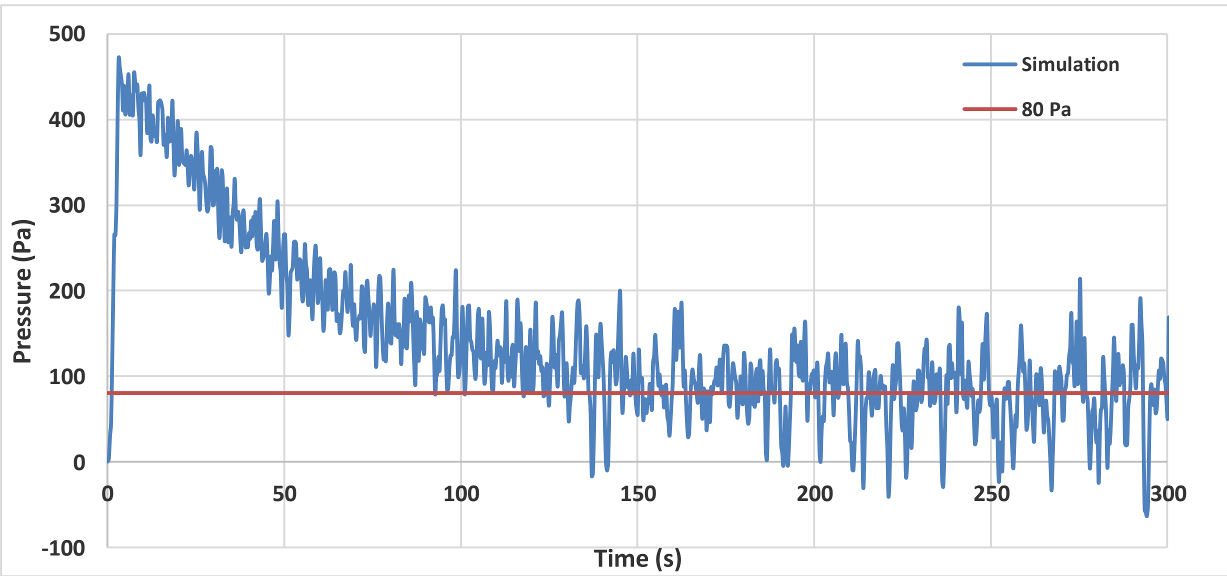


Figure 30. Pressure vs time graph for constant MLRPUA fire simulation for local ventilation network.

The average value of steady pressure in the room is 80 Pa (figure 30) which is near to the average pressure value (94 Pa) predicted in the case of varying MLRPUA (figure 27).

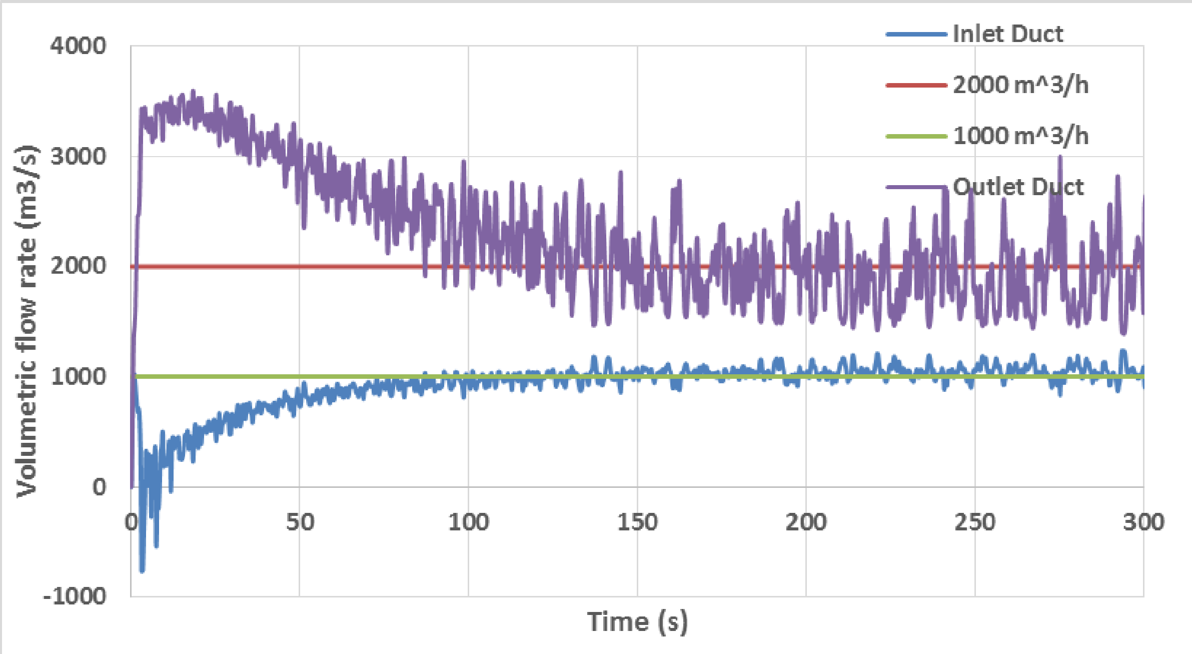


Figure 31. Volumetric flow rate vs time graph for constant MLRPUA fire simulation for local ventilation.

From figure 31, the average value of steady inlet volumetric flow in the room is 1000 m^3/h which is close to average inlet volumetric flow 1130 m^3/h in the case of varying MLRPUA (figure 28). The average value of steady outlet volumetric flow in the room is 2000 m^3/h which is close to average outlet volumetric flow 2300 m^3/h in the case of varying MLRPUA (figure 29).

IV.2.3 Global Ventilation Network Simulation with ramped MLRPUA

The validated global ventilation network as shown in figure 26 has been used for fire simulation in which mass loss rate per unit area obtained from the experimental data has been ramped in FDS to see its effect on the pressure and volumetric flow rates in the duct directly connected to the room "L3". Results here does not fairly match with the experimental data as constant volumetric flow rate fan behaves very differently from the fan having quadtratic nature.

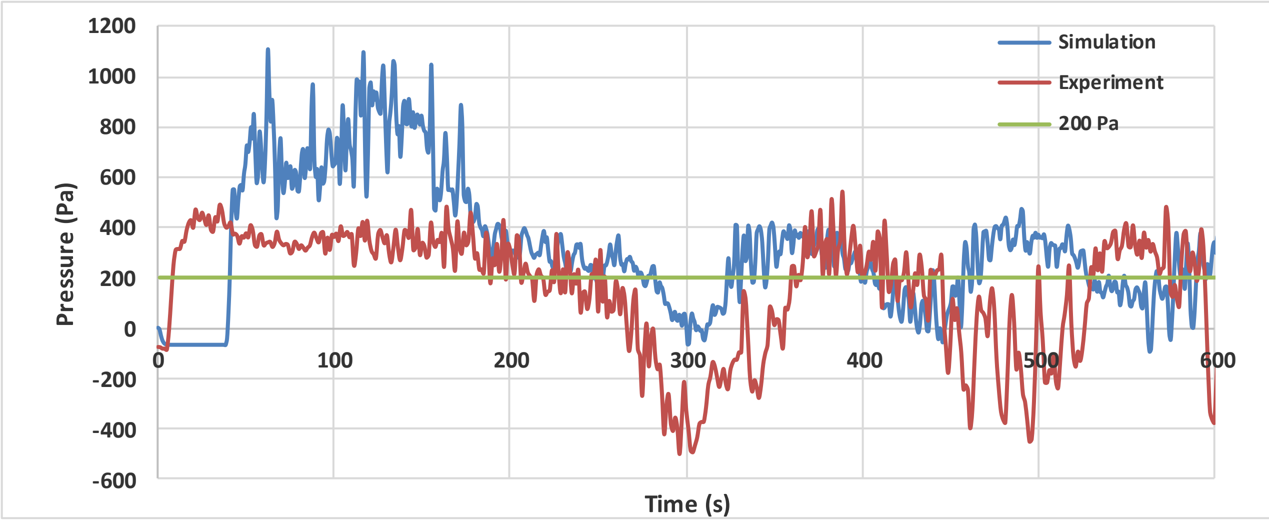


Figure 32. Pressure vs time graph of experimental data and simulation for global ventilation network (Varying MLRPUA).

It can be noted from the figure 32 that with constant volume flow rate of fan, the pressure in the room has not reached the peak negative values in the simulation. Moreover with the given inputs, the simulation has not been able to capture the pressure fluctuation trend properly. After 200 seconds, the simulation pressure follows the cyclic trend of rise and fall with mean pressure 200 Pa. The positive and negative fluctuation from mean pressure in simulation has happened largely due to varying mass loss rate as there is no quadratic nature of interaction between pressure induced in room and constant volume flow rate fan.

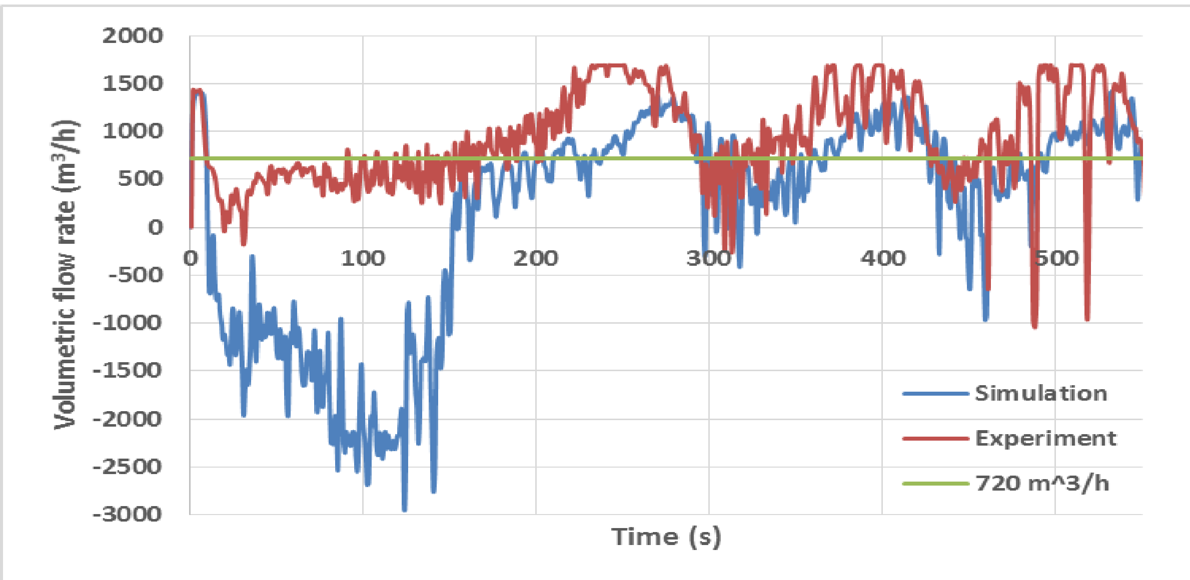


Figure 33. Volumetric flow rate vs time graph of simulation and experiment for inlet duct for global ventilation network (Varying MLRPUA).

From figure 33, it can be noted that in steady state with given inputs, FDS is able to follow the trend of volumetric flow rate for the inlet duct but under predicts the magnitude of the flow. Quadratic nature of fans is expected to give better results for the volumetric flow rates in the duct as shown in figure 27.

It was also noted in the simulation that the volumetric flow rate in the section of duct between nodes N2 and N1 which has inlet fan, did not change at all and remained at constant value of 5.97 m^3/s. Same observation was made for section of duct between nodes N12 and N14 which has outlet fan and here also the volumetric flow rate remained constant at 7.82 m^3/s. This clearly shows that this section of the network was not affected by the fire effects and maintained constant volume flow rate. For nodes location refer figure 26.

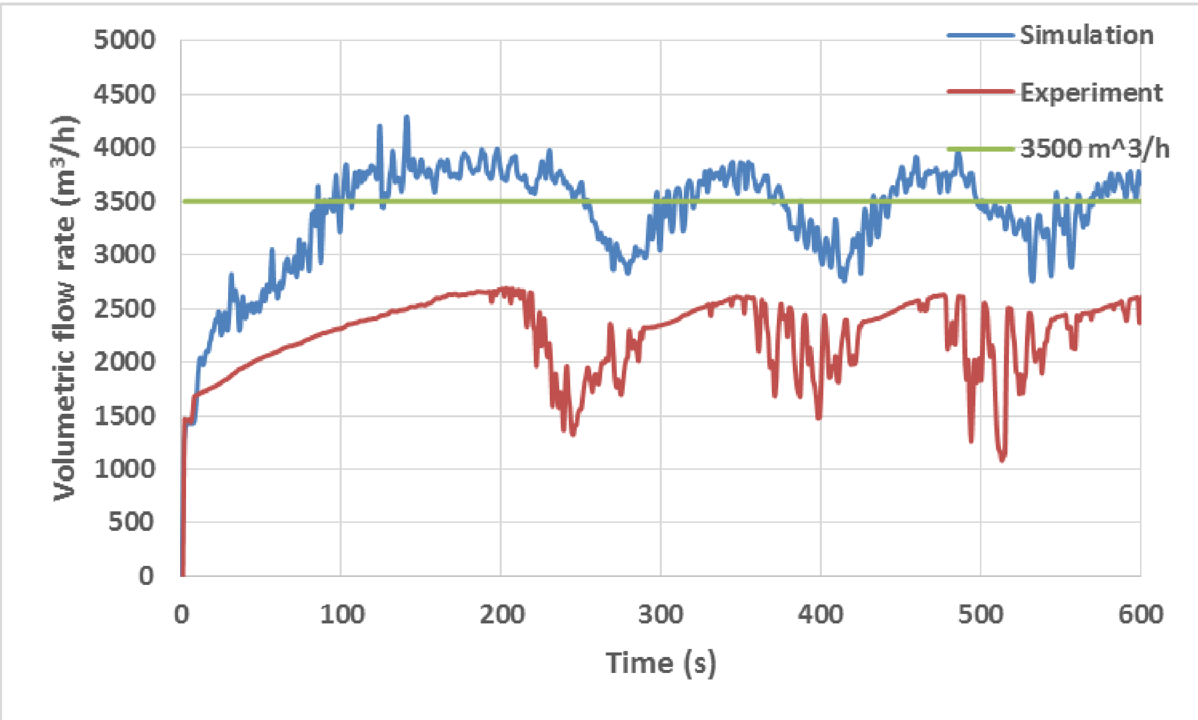


Figure 34. Volumetric flow rate vs time graph of simulation and experiment for outlet duct for global ventilation network (Varying MLRPUA).

With the given inputs, FDS has over-predicted the volumetric flow rate of outlet duct (figure 34). Probable error in the measurement of the volumetric flow rate in the outlet duct during the experiment also must have widen the gap of digression with respect to the simulation results for outlet duct connected to the room.

IV.2.4 Global Ventilation Network Simulation with fixed MLRPUA

In this case the average value of mass loss rate per unit area (0.02825 kg/s.m^2) has been used for fire in the simulation for global ventilation network.

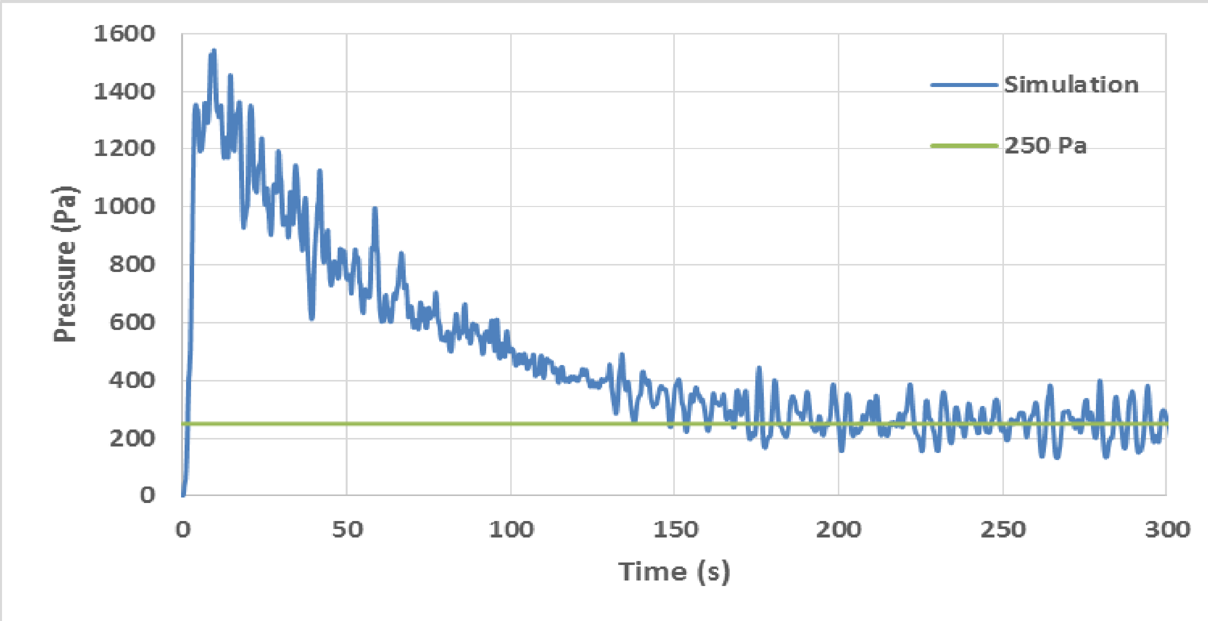


Figure 35. Pressure vs time graph for constant MLRPUA for global ventilation network.

The average value of steady pressure in the room is 250 Pa (figure 35) which is near to the average pressure value (200 Pa) predicted in the case of varying MLRPUA for global ventilation network with fire (figure 32).

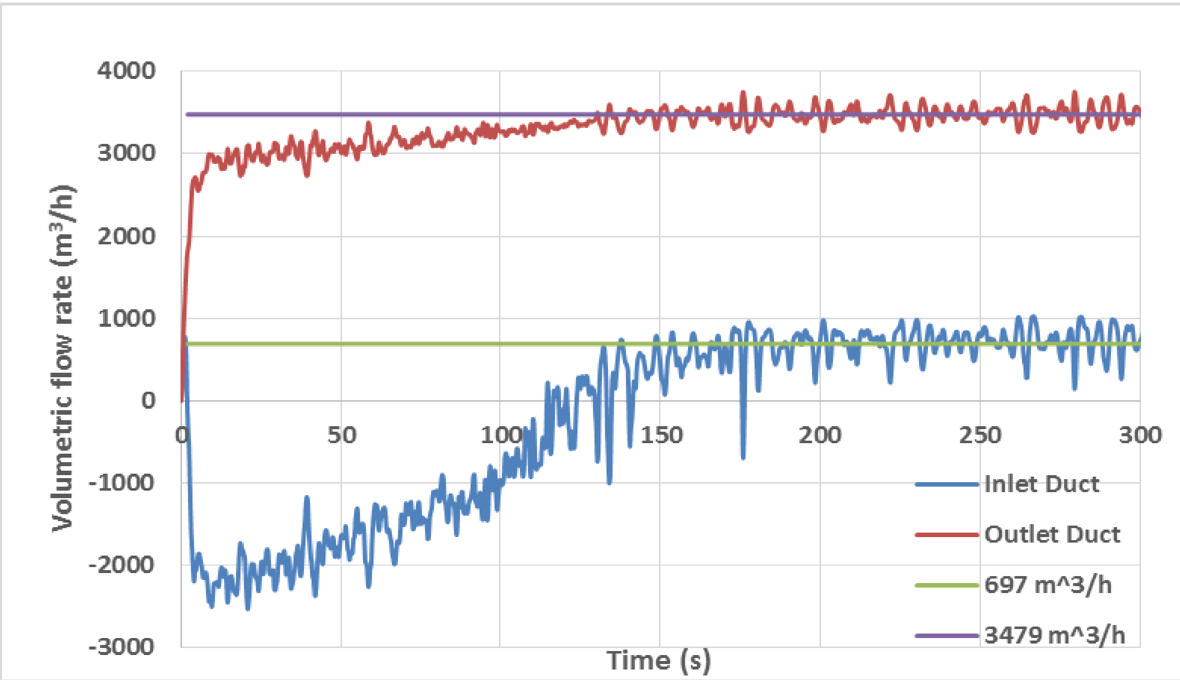


Figure 36. Volumetric flow rate vs time graph for constant MLRPUA for global ventilation network.

From figure 36, it can be seen that the average value of steady inlet volumetric flow in the room is 697 m^3/h which is close to average inlet volumetric flow 720 m^3/h in the case of varying MLRPUA (figure 33). The average value of steady outlet volumetric flow in the room is 3479 m^3/h which is close to average outlet volumetric flow 3500 m^3/h in the case of varying MLRPUA (figure 34).

V. Discussion

Sensitivity studies before validating the ventilation network have provided an indication as how sensitive input data are for the various results. The magnitude of pressure in the room is directly affected by increasing the length of the duct. In our case, the pressure of the room being negative, the pressure has become more negative when the length of the ducts were increased. Moreover, with increase in length of ducts the volumetric flow rate decreases although by very small percentage due the roughness which acts for more length of the flow when length is increased. In case when roughness is assigned zero value for the ducts, then steady pressure in the room created by different length of ducts remains almost the same (condition: fittings are not altered for ducts and only length has been increased). To avoid such results, roughness should be assigned some reasonable value before carrying out the simulations. If this is not done then varying the lengths of the ducts in the simulation will not give the different results as in real case ducts have roughness and pressure drop in ducts are affected by the length of ducts. It was also brought out from the sensitivity study that in case of fluid having density around 1 like air, the variation of roughness does not bring significant difference in the pressure created in the room nor in the volumetric flow rate in ducts. The area of leakage is also one of the most influential factor for pressure change in the room as more is the area of leakage, less is the magnitude of pressure expected to develop in the room by mechanical system carrying either positive or negative pressurization. The variation of node height (z-coordinate) does bring change in the pressure profile although by small percentage. So at least z-coordinates of nodes should be known or reasonable value must be assumed so that its effect can be incorporated in the simulations.

As in reality the volumetric flow rate of fan gets altered with the pressure of fluid on the fan blades, so as far as possible the stall pressure of the fan with its volume flow rate at zero static pressure must be known or reasonable assumption should be made for their values to carry HVAC simulations in FDS. If experimental data for pressure variation against the volumetric flow rate is known for a room and connected ducts then values for possible quadratic fan characteristics can be found. If the data is very much scattered then two to three cases of fan curve can be considered in the trail simulations for fan and finally one parameter for the fan should be chosen which can replicate the fan operation in the best possible way. FDS also provides the option of ramping the data of pressure variation with volume flow rate which can also be used for simulations.

In case of non-fire simulations (for both local and global ventilation network) it has been successfully demonstrated through the results that FDS with the given inputs, especially with the calculated values of loss coefficients for various ducts, is able to validate the pressure and volumetric flow conditions with the acceptable errors. The data related to volumetric flow rate and nodes pressure play the crucial role in FDS to give acceptable results. In cases where such data are not available or are insufficient, the network can be modified as done for global ventilation network. With such modification, the loss coefficient of desired ducts can be calculated and feed into FDS code.

In case of fire simulations (local ventilation network case with varying MLRPUA), as data for pressure profile and volumetric flow for the duct directly connected to the room were available, the room was considered in isolation. In this case, the other end of the duct was assumed to be ambient (0 Pa) and loss coefficient was calculated on this ambient node assumption. With this configuration and quadratic fan characteristics, pressure variation with time during the fire has been successfully validated in FDS. Volumetric flow rate for inlet duct has also been replicated in simulation with acceptable accuracy, but volumetric flow rate for outlet duct has not been reproduced in simulation with reasonable accuracy. The probable cause for this digression can be error in the measurement of volumetric flow rate of outlet duct during the experiment. Moreover, with fixed (average) MLRPUA fire simulation it has also been further demonstrated that mean pressure and volumetric flow rate profile in the room with the varying MLRPUA matches with the pressure and volumetric flow rate profile with average fixed (average) MLRPUA for local ventilation network.

In case of fire simulations (global ventilation network case with varying MLRPUA), as the data for quadratic behavior of the fan which powered the global ventilation network was not able to be extracted from the available data, it was assigned the fixed volume flow as discussed. With such configuration, FDS is able to capture the trend of rise and fall of pressure but does not capture the peak values of positive and negative pressures in the room. Up to some extent it follows the trend of inlet volumetric flow rate but under predicts the peak values of positive and negative volumetric flow rate. Here the cyclic trend in simulation is caused by the varying MLRPUA as the fan is not quadratic with which it could have adjusted its flow. With fixed volume flow of the fan, a mean value of pressure and volumetric flow (inlet duct) can been seen in the results, and the rise and fall around this mean value is caused by varying MLRPUA. Here also the volumetric flow rate in the outlet duct in simulation does match with the experimental values. Moreover, with fixed (average) MLRPUA fire simulation it has also been further demonstrated that mean pressure and volumetric flow rate profile in the room with varying MLRPUA matches with the pressure and volumetric flow rate profile with fixed (average) MLRPUA for global ventilation network.

It is also important to mention here that caution has to be taken to analyze the experimental values related to pressure, volumetric flow rate and mass loss rate. Evident digression in data from the accepted range of values should be identified and discarded if their exclusion does not affect the result or gives erratic results in simulations. In the given case, when mass loss rate was calculated from mass variation with respect to time, there were negative values of mass loss rate which are not possible in case of burning. The negative mass loss rate values were replaced by zeros to avoid the error in simulation. Such modification in values does have effects in the overall results and must be kept in check while analyzing the results. The ramped mass loss rate and corresponding heat release rate in FDS which happens in the discretized form leads to more frequent fluctuations in pressure and volumetric flow rate profiles and can be noted in the various results.

VI. Conclusion

Coupling of HVAC model based on the MELCOR algorithm with FDS has significantly improved the capability of FDS to model simple to complex ventilation network with acceptable predictions. It has been demonstrated through various results that the FDS(6) can successfully simulate a tightly sealed room connected to a mechanical ventilation, with and without fire, based on the kind of inputs given to it. Parameters for fan curve play a very important role to simulate fire and non-fire conditions.

In order to validate a ventilation network without fire, constant volume flow characteristics assigned to the fan would produce better results than the quadratic volume flow parameters chosen from the experimental values. In this case there is no counter flow of fluid like fire gas fluid which can bring change in the values of volumetric flow rate of a duct and thus volumetric flow rate produced by solving the governing equations for the HVAC model give the results matching the reality. This has been successfully demonstrated in the case of global ventilation network which was complex and where the fan with constant volume flow produced results for the pressure and volumetric flow rate in the duct connected to the considered room with less errors than compared to local ventilation network which had the quadratic fan characteristics obtained from the experimental values. Moreover, to validate a ventilation network with the effects of fire, the quadratic fan curve would produce better results of interaction of ventilation network with fire than the constant volume flow parameter. It is because the fan with quadratic characteristics can adjust its volumetric flow rate with respect to pressure created across its blade. In local ventilation network case, as quadratic fan characteristics were used, the results of interaction of ventilation with fire in terms of pressure and volumetric flow rate were better than global ventilation network where the constant volume flow for the fan was used. It is expected that the global ventilation network with quadratic fan characteristics will produce better results. Unfortunately, from the available data the values for quadratic fan characteristics could not be extracted for the global ventilation network.

It is concluded that the pressure and volumetric flow profile given by FDS can match the reality with some exceptions based on the HVAC parameters chosen for fire and non-fire simulations. It is also important to note that all the input parameters like duct length, roughness, area of leakage, nodes coordinates etc. should be given reasonable values if actual data are not available, to get the best possible results from FDS.

Future work can involve the validation of similar test cases of confined room with mechanical ventilation. Test cases can involve simple to complex setups involving single to multiple rooms on single floor to multiple floors. Multi-floor buildings will make the case more complex as buoyancy will play its role once smoke overcomes the inlet air pressure and starts moving vertically up through ducts.

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Lastly, I would also like to express thanks to my family for always being there for me.

It would have been impossible without everyone’s effort and blessings.

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Appendix

Sample FDS input file

```
&HEAD CHID='8B1M1', TITLE='Room with fire and complex ventilation network, sample run'
/

&MESH IJK= 90,72,60, XB= 0.0, 6.0, 0.0, 5.0, 0.0, 4.0/

&TIME T_END=500.0 /

&MISC HUMIDITY=0.0 /

&REAC FUEL = 'N-HEPTANE', SOOT_YIELD = 0.015, CO_YIELD = 0.008,
HEAT_OF_COMBUSTION = 46200. /

&SURF ID = 'FIRE', MLRPUA = 0.119047, RAMP_Q = 'fireramp', COLOR = 'RED'/

&VENT XB = 2.68, 3.32, 2.18, 2.82, 0.4, 0.4, SURF_ID = 'FIRE', IOR = +3/

&OBST XB = 2.68, 3.32, 2.18, 2.82, 0.0, 0.4 /

&RAMP ID = 'fireramp' , T = 1 , F = 0 /
&RAMP ID = 'fireramp' , T = 2 , F = 0 /
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&RAMP	ID = 'fireramp'	,	T =	263	,	F =	0.066667	/
&RAMP	ID = 'fireramp'	,	T =	264	,	F =	0.066667	/
&RAMP	ID = 'fireramp'	,	T =	265	,	F =	0	/
&RAMP	ID = 'fireramp'	,	T =	266	,	F =	0.099213	/
&RAMP	ID = 'fireramp'	,	T =	267	,	F =	0.133333	/
&RAMP	ID = 'fireramp'	,	T =	268	,	F =	0	/
&RAMP	ID = 'fireramp'	,	T =	269	,	F =	0	/
&RAMP	ID = 'fireramp'	,	T =	270	,	F =	0.0336	/
&RAMP	ID = 'fireramp'	,	T =	271	,	F =	0.165354	/
&RAMP	ID = 'fireramp'	,	T =	272	,	F =	0.066667	/
&RAMP	ID = 'fireramp'	,	T =	273	,	F =	0.1	/
&RAMP	ID = 'fireramp'	,	T =	274	,	F =	0.066667	/
&RAMP	ID = 'fireramp'	,	T =	275	,	F =	0.101613	/
&RAMP	ID = 'fireramp'	,	T =	276	,	F =	0.099213	/
&RAMP	ID = 'fireramp'	,	T =	277	,	F =	0.033333	/
&RAMP	ID = 'fireramp'	,	T =	278	,	F =	0.133333	/
&RAMP	ID = 'fireramp'	,	T =	279	,	F =	0.0672	/
&RAMP	ID = 'fireramp'	,	T =	280	,	F =	0.0336	/
&RAMP	ID = 'fireramp'	,	T =	281	,	F =	0.1	/
&RAMP	ID = 'fireramp'	,	T =	282	,	F =	0.1008	/
&RAMP	ID = 'fireramp'	,	T =	283	,	F =	0.168	/
&RAMP	ID = 'fireramp'	,	T =	284	,	F =	0.169355	/
&RAMP	ID = 'fireramp'	,	T =	285	,	F =	0.033333	/
&RAMP	ID = 'fireramp'	,	T =	286	,	F =	0.0672	/
&RAMP	ID = 'fireramp'	,	T =	287	,	F =	0.237097	/
&RAMP	ID = 'fireramp'	,	T =	288	,	F =	0	/
&RAMP	ID = 'fireramp'	,	T =	289	,	F =	0.1	/
&RAMP	ID = 'fireramp'	,	T =	290	,	F =	0.270968	/
&RAMP	ID = 'fireramp'	,	T =	291	,	F =	0.165354	/
&RAMP	ID = 'fireramp'	,	T =	292	,	F =	0.2	/
&RAMP	ID = 'fireramp'	,	T =	293	,	F =	0.1344	/
&RAMP	ID = 'fireramp'	,	T =	294	,	F =	0.1008	/
&RAMP	ID = 'fireramp'	,	T =	295	,	F =	0.666667	/
&RAMP	ID = 'fireramp'	,	T =	296	,	F =	0	/
&RAMP	ID = 'fireramp'	,	T =	297	,	F =	0.066667	/
&RAMP	ID = 'fireramp'	,	T =	298	,	F =	0.3024	/
&RAMP	ID = 'fireramp'	,	T =	299	,	F =	0.406452	/
&RAMP	ID = 'fireramp'	,	T =	300	,	F =	0.033071	/
&RAMP	ID = 'fireramp'	,	T =	301	,	F =	0.1	/
&RAMP	ID = 'fireramp'	,	T =	302	,	F =	0.9408	/
&RAMP	ID = 'fireramp'	,	T =	303	,	F =	0.0336	/

&RAMP	ID = 'fireramp'	,	T =	304	,	F =	0	/
&RAMP	ID = 'fireramp'	,	T =	305	,	F =	0.2	/
&RAMP	ID = 'fireramp'	,	T =	306	,	F =	0.2352	/
&RAMP	ID = 'fireramp'	,	T =	307	,	F =	0.7728	/
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&RAMP	ID = 'fireramp'	,	T =	309	,	F =	0.033333	/
&RAMP	ID = 'fireramp'	,	T =	310	,	F =	0.304839	/
&RAMP	ID = 'fireramp'	,	T =	311	,	F =	0.165354	/
&RAMP	ID = 'fireramp'	,	T =	312	,	F =	0.366667	/
&RAMP	ID = 'fireramp'	,	T =	313	,	F =	0.5	/
&RAMP	ID = 'fireramp'	,	T =	314	,	F =	0.066667	/
&RAMP	ID = 'fireramp'	,	T =	315	,	F =	0.406452	/
&RAMP	ID = 'fireramp'	,	T =	316	,	F =	0.462992	/
&RAMP	ID = 'fireramp'	,	T =	317	,	F =	0.066667	/
&RAMP	ID = 'fireramp'	,	T =	318	,	F =	0.3024	/
&RAMP	ID = 'fireramp'	,	T =	319	,	F =	0.203226	/
&RAMP	ID = 'fireramp'	,	T =	320	,	F =	0.233333	/
&RAMP	ID = 'fireramp'	,	T =	321	,	F =	0.5	/
&RAMP	ID = 'fireramp'	,	T =	322	,	F =	0.3024	/
&RAMP	ID = 'fireramp'	,	T =	323	,	F =	0.297638	/
&RAMP	ID = 'fireramp'	,	T =	324	,	F =	0.366667	/
&RAMP	ID = 'fireramp'	,	T =	325	,	F =	0.198425	/
&RAMP	ID = 'fireramp'	,	T =	326	,	F =	0.566667	/
&RAMP	ID = 'fireramp'	,	T =	327	,	F =	0.2	/
&RAMP	ID = 'fireramp'	,	T =	328	,	F =	0.2688	/
&RAMP	ID = 'fireramp'	,	T =	329	,	F =	0.466667	/
&RAMP	ID = 'fireramp'	,	T =	330	,	F =	0.198425	/
&RAMP	ID = 'fireramp'	,	T =	331	,	F =	0.5	/
&RAMP	ID = 'fireramp'	,	T =	332	,	F =	0.5	/
&RAMP	ID = 'fireramp'	,	T =	333	,	F =	0.1344	/
&RAMP	ID = 'fireramp'	,	T =	334	,	F =	0.3024	/
&RAMP	ID = 'fireramp'	,	T =	335	,	F =	0.3	/
&RAMP	ID = 'fireramp'	,	T =	336	,	F =	0.39685	/
&RAMP	ID = 'fireramp'	,	T =	337	,	F =	0.4032	/
&RAMP	ID = 'fireramp'	,	T =	338	,	F =	0.266667	/
&RAMP	ID = 'fireramp'	,	T =	339	,	F =	0.372581	/
&RAMP	ID = 'fireramp'	,	T =	340	,	F =	0.466667	/
&RAMP	ID = 'fireramp'	,	T =	341	,	F =	0.4368	/
&RAMP	ID = 'fireramp'	,	T =	342	,	F =	0.237097	/
&RAMP	ID = 'fireramp'	,	T =	343	,	F =	0.266667	/
&RAMP	ID = 'fireramp'	,	T =	344	,	F =	0.3696	/
&RAMP	ID = 'fireramp'	,	T =	345	,	F =	0.3696	/
&RAMP	ID = 'fireramp'	,	T =	346	,	F =	0.2	/
&RAMP	ID = 'fireramp'	,	T =	347	,	F =	0.566667	/
&RAMP	ID = 'fireramp'	,	T =	348	,	F =	0.4	/
&RAMP	ID = 'fireramp'	,	T =	349	,	F =	0.2016	/

&RAMP	ID = 'fireramp'	,	T =	350	,	F =	0.3	/
&RAMP	ID = 'fireramp'	,	T =	351	,	F =	0.36378	/
&RAMP	ID = 'fireramp'	,	T =	352	,	F =	0.566667	/
&RAMP	ID = 'fireramp'	,	T =	353	,	F =	0.336	/
&RAMP	ID = 'fireramp'	,	T =	354	,	F =	0.203226	/
&RAMP	ID = 'fireramp'	,	T =	355	,	F =	0.2	/
&RAMP	ID = 'fireramp'	,	T =	356	,	F =	0.4368	/
&RAMP	ID = 'fireramp'	,	T =	357	,	F =	0.203226	/
&RAMP	ID = 'fireramp'	,	T =	358	,	F =	0.36378	/
&RAMP	ID = 'fireramp'	,	T =	359	,	F =	0.366667	/
&RAMP	ID = 'fireramp'	,	T =	360	,	F =	0.2	/
&RAMP	ID = 'fireramp'	,	T =	361	,	F =	0.2688	/
&RAMP	ID = 'fireramp'	,	T =	362	,	F =	0.2688	/
&RAMP	ID = 'fireramp'	,	T =	363	,	F =	0.333333	/
&RAMP	ID = 'fireramp'	,	T =	364	,	F =	0.166667	/
&RAMP	ID = 'fireramp'	,	T =	365	,	F =	0.166667	/
&RAMP	ID = 'fireramp'	,	T =	366	,	F =	0.2016	/
&RAMP	ID = 'fireramp'	,	T =	367	,	F =	0.233333	/
&RAMP	ID = 'fireramp'	,	T =	368	,	F =	0.330709	/
&RAMP	ID = 'fireramp'	,	T =	369	,	F =	0.2688	/
&RAMP	ID = 'fireramp'	,	T =	370	,	F =	0.168	/
&RAMP	ID = 'fireramp'	,	T =	371	,	F =	0.203226	/
&RAMP	ID = 'fireramp'	,	T =	372	,	F =	0.1344	/
&RAMP	ID = 'fireramp'	,	T =	373	,	F =	0.1008	/
&RAMP	ID = 'fireramp'	,	T =	374	,	F =	0.165354	/
&RAMP	ID = 'fireramp'	,	T =	375	,	F =	0.133333	/
&RAMP	ID = 'fireramp'	,	T =	376	,	F =	0.2	/
&RAMP	ID = 'fireramp'	,	T =	377	,	F =	0.133333	/
&RAMP	ID = 'fireramp'	,	T =	378	,	F =	0.067742	/
&RAMP	ID = 'fireramp'	,	T =	379	,	F =	0.165354	/
&RAMP	ID = 'fireramp'	,	T =	380	,	F =	0.1008	/
&RAMP	ID = 'fireramp'	,	T =	381	,	F =	0.033333	/
&RAMP	ID = 'fireramp'	,	T =	382	,	F =	0.135484	/
&RAMP	ID = 'fireramp'	,	T =	383	,	F =	0.264567	/
&RAMP	ID = 'fireramp'	,	T =	384	,	F =	0.2	/
&RAMP	ID = 'fireramp'	,	T =	385	,	F =	0.168	/
&RAMP	ID = 'fireramp'	,	T =	386	,	F =	0.1008	/
&RAMP	ID = 'fireramp'	,	T =	387	,	F =	0.132283	/
&RAMP	ID = 'fireramp'	,	T =	388	,	F =	0.066667	/
&RAMP	ID = 'fireramp'	,	T =	389	,	F =	0.033333	/
&RAMP	ID = 'fireramp'	,	T =	390	,	F =	0.066667	/
&RAMP	ID = 'fireramp'	,	T =	391	,	F =	0.3024	/
&RAMP	ID = 'fireramp'	,	T =	392	,	F =	0.135484	/
&RAMP	ID = 'fireramp'	,	T =	393	,	F =	0.166667	/
&RAMP	ID = 'fireramp'	,	T =	394	,	F =	0.1008	/
&RAMP	ID = 'fireramp'	,	T =	395	,	F =	0.102439	/

&RAMP	ID = 'fireramp'	,	T =	396	,	F =	0.133333 /
&RAMP	ID = 'fireramp'	,	T =	397	,	F =	0.0672 /
&RAMP	ID = 'fireramp'	,	T =	398	,	F =	0.1 /
&RAMP	ID = 'fireramp'	,	T =	399	,	F =	0.066142 /
&RAMP	ID = 'fireramp'	,	T =	400	,	F =	0.133333 /
&RAMP	ID = 'fireramp'	,	T =	401	,	F =	0.2 /
&RAMP	ID = 'fireramp'	,	T =	402	,	F =	0.033871 /
&RAMP	ID = 'fireramp'	,	T =	403	,	F =	0.132283 /
&RAMP	ID = 'fireramp'	,	T =	404	,	F =	0 /
&RAMP	ID = 'fireramp'	,	T =	405	,	F =	0.066667 /
&RAMP	ID = 'fireramp'	,	T =	406	,	F =	0.2016 /
&RAMP	ID = 'fireramp'	,	T =	407	,	F =	0.203226 /
&RAMP	ID = 'fireramp'	,	T =	408	,	F =	0.165354 /
&RAMP	ID = 'fireramp'	,	T =	409	,	F =	0.1008 /
&RAMP	ID = 'fireramp'	,	T =	410	,	F =	0 /
&RAMP	ID = 'fireramp'	,	T =	411	,	F =	0.101613 /
&RAMP	ID = 'fireramp'	,	T =	412	,	F =	0.066667 /
&RAMP	ID = 'fireramp'	,	T =	413	,	F =	0.033333 /
&RAMP	ID = 'fireramp'	,	T =	414	,	F =	0.1008 /
&RAMP	ID = 'fireramp'	,	T =	415	,	F =	0.133333 /
&RAMP	ID = 'fireramp'	,	T =	416	,	F =	0.099213 /
&RAMP	ID = 'fireramp'	,	T =	417	,	F =	0.1 /
&RAMP	ID = 'fireramp'	,	T =	418	,	F =	0.168 /
&RAMP	ID = 'fireramp'	,	T =	419	,	F =	0.1344 /
&RAMP	ID = 'fireramp'	,	T =	420	,	F =	0.101613 /
&RAMP	ID = 'fireramp'	,	T =	421	,	F =	0.266667 /
&RAMP	ID = 'fireramp'	,	T =	422	,	F =	0.0336 /
&RAMP	ID = 'fireramp'	,	T =	423	,	F =	0.1008 /
&RAMP	ID = 'fireramp'	,	T =	424	,	F =	0.166667 /
&RAMP	ID = 'fireramp'	,	T =	425	,	F =	0.133333 /
&RAMP	ID = 'fireramp'	,	T =	426	,	F =	0.4032 /
&RAMP	ID = 'fireramp'	,	T =	427	,	F =	0.135484 /
&RAMP	ID = 'fireramp'	,	T =	428	,	F =	0.166667 /
&RAMP	ID = 'fireramp'	,	T =	429	,	F =	0.2352 /
&RAMP	ID = 'fireramp'	,	T =	430	,	F =	0.3024 /
&RAMP	ID = 'fireramp'	,	T =	431	,	F =	0.233333 /
&RAMP	ID = 'fireramp'	,	T =	432	,	F =	0.198425 /
&RAMP	ID = 'fireramp'	,	T =	433	,	F =	0.2352 /
&RAMP	ID = 'fireramp'	,	T =	434	,	F =	0.233333 /
&RAMP	ID = 'fireramp'	,	T =	435	,	F =	0.203226 /
&RAMP	ID = 'fireramp'	,	T =	436	,	F =	0.266667 /
&RAMP	ID = 'fireramp'	,	T =	437	,	F =	0.336 /
&RAMP	ID = 'fireramp'	,	T =	438	,	F =	0.2016 /
&RAMP	ID = 'fireramp'	,	T =	439	,	F =	0.36378 /
&RAMP	ID = 'fireramp'	,	T =	440	,	F =	0.333333 /
&RAMP	ID = 'fireramp'	,	T =	441	,	F =	0.1344 /

&RAMP	ID = 'fireramp'	,	T =	442	,	F =	0.4704 /
&RAMP	ID = 'fireramp'	,	T =	443	,	F =	0.270968 /
&RAMP	ID = 'fireramp'	,	T =	444	,	F =	0.433333 /
&RAMP	ID = 'fireramp'	,	T =	445	,	F =	0.4032 /
&RAMP	ID = 'fireramp'	,	T =	446	,	F =	0.7728 /
&RAMP	ID = 'fireramp'	,	T =	447	,	F =	0.1 /
&RAMP	ID = 'fireramp'	,	T =	448	,	F =	0.133333 /
&RAMP	ID = 'fireramp'	,	T =	449	,	F =	0.3696 /
&RAMP	ID = 'fireramp'	,	T =	450	,	F =	0.3024 /
&RAMP	ID = 'fireramp'	,	T =	451	,	F =	0.36378 /
&RAMP	ID = 'fireramp'	,	T =	452	,	F =	0.3 /
&RAMP	ID = 'fireramp'	,	T =	453	,	F =	0.4032 /
&RAMP	ID = 'fireramp'	,	T =	454	,	F =	0.067742 /
&RAMP	ID = 'fireramp'	,	T =	455	,	F =	0.628346 /
&RAMP	ID = 'fireramp'	,	T =	456	,	F =	0.133333 /
&RAMP	ID = 'fireramp'	,	T =	457	,	F =	0.9072 /
&RAMP	ID = 'fireramp'	,	T =	458	,	F =	0.1344 /
&RAMP	ID = 'fireramp'	,	T =	459	,	F =	0.165354 /
&RAMP	ID = 'fireramp'	,	T =	460	,	F =	0.866667 /
&RAMP	ID = 'fireramp'	,	T =	461	,	F =	0.266667 /
&RAMP	ID = 'fireramp'	,	T =	462	,	F =	0.1344 /
&RAMP	ID = 'fireramp'	,	T =	463	,	F =	0.2016 /
&RAMP	ID = 'fireramp'	,	T =	464	,	F =	0.533333 /
&RAMP	ID = 'fireramp'	,	T =	465	,	F =	0.266667 /
&RAMP	ID = 'fireramp'	,	T =	466	,	F =	0.4032 /
&RAMP	ID = 'fireramp'	,	T =	467	,	F =	0.4368 /
&RAMP	ID = 'fireramp'	,	T =	468	,	F =	0.666667 /
&RAMP	ID = 'fireramp'	,	T =	469	,	F =	0.266667 /
&RAMP	ID = 'fireramp'	,	T =	470	,	F =	0 /
&RAMP	ID = 'fireramp'	,	T =	471	,	F =	0.677419 /
&RAMP	ID = 'fireramp'	,	T =	472	,	F =	0.233333 /
&RAMP	ID = 'fireramp'	,	T =	473	,	F =	0.266667 /
&RAMP	ID = 'fireramp'	,	T =	474	,	F =	0.372581 /
&RAMP	ID = 'fireramp'	,	T =	475	,	F =	0.264567 /
&RAMP	ID = 'fireramp'	,	T =	476	,	F =	0.533333 /
&RAMP	ID = 'fireramp'	,	T =	477	,	F =	0.3024 /
&RAMP	ID = 'fireramp'	,	T =	478	,	F =	0.336 /
&RAMP	ID = 'fireramp'	,	T =	479	,	F =	0.3 /
&RAMP	ID = 'fireramp'	,	T =	480	,	F =	0.429921 /
&RAMP	ID = 'fireramp'	,	T =	481	,	F =	0.266667 /
&RAMP	ID = 'fireramp'	,	T =	482	,	F =	0.336 /
&RAMP	ID = 'fireramp'	,	T =	483	,	F =	0.304839 /
&RAMP	ID = 'fireramp'	,	T =	484	,	F =	0.297638 /
&RAMP	ID = 'fireramp'	,	T =	485	,	F =	0.366667 /
&RAMP	ID = 'fireramp'	,	T =	486	,	F =	0.2016 /
&RAMP	ID = 'fireramp'	,	T =	487	,	F =	0.372581 /

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&RAMP    ID = 'fireramp'    ,    T =    488    ,    F =    0.166667    /
&RAMP    ID = 'fireramp'    ,    T =    489    ,    F =    0.2688    /
&RAMP    ID = 'fireramp'    ,    T =    490    ,    F =    0.270968    /
&RAMP    ID = 'fireramp'    ,    T =    491    ,    F =    0.333333    /
&RAMP    ID = 'fireramp'    ,    T =    492    ,    F =    0.3    /
&RAMP    ID = 'fireramp'    ,    T =    493    ,    F =    0.133333    /
&RAMP    ID = 'fireramp'    ,    T =    494    ,    F =    0.237097    /
&RAMP    ID = 'fireramp'    ,    T =    495    ,    F =    0.266667    /
&RAMP    ID = 'fireramp'    ,    T =    496    ,    F =    0.033333    /
&RAMP    ID = 'fireramp'    ,    T =    497    ,    F =    0.1    /
&RAMP    ID = 'fireramp'    ,    T =    498    ,    F =    0.101613    /
&RAMP    ID = 'fireramp'    ,    T =    499    ,    F =    0.2    /
&RAMP    ID = 'fireramp'    ,    T =    500    ,    F =    0.166667    /

&MATL ID='CONCRETE',
FYI='PRISME-SOURCE Test',
SPECIFIC_HEAT=0.88,
CONDUCTIVITY=1.4,
DENSITY=2300.0,
EMISSIVITY=0.85/

&SURF ID='wall',
COLOR = 'BLACK',
BACKING='VOID',
MATL_ID(1,1)='CONCRETE',
MATL_MASS_FRACTION(1,1)=1.0,
THICKNESS(1:1)=0.05/

&SURF ID='wall', TRANSPARENCY =0.1./
&OBST XB = 0.0, 6.0, 0.0, 0.1, 0.0, 4.0, SURF_ID = 'wall'  /
&OBST XB = 0.0, 0.1, 0.0, 5.0, 0.0, 4.0, SURF_ID = 'wall'  /
&OBST XB = 0.0, 6.0, 4.9, 5.0, 0.0, 4.0, SURF_ID = 'wall'  /
&OBST XB = 5.9, 6.0, 0.0, 5.0, 0.0, 4.0, SURF_ID = 'wall'  /
&OBST XB = 0.0, 6.0, 0.0, 5.0, 3.9, 4.0,  SURF_ID = 'wall' / Ceiling
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&OBST XB = 0.0, 6.0, 0.0, 5.0, 0.0, 0.1, SURF_ID = 'wall' / Floor

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&ZONE XB = 0.0, 6.0, 0.0, 5.0, 0.0, 4.0, LEAK_AREA (0) = 0.0005 / Room L3 made zone1 and leak to outside through 0.0005m2

&SURF ID = 'LEAK', LEAK_PATH = 1,0/

&VENT XB = 5.9, 5.9, 2.4, 2.6, 0.1, 0.3, COLOR = 'GREEN', SURF_ID = 'LEAK', IOR = -1/

&VENT XB = 6.0, 6.0, 2.4, 2.6, 0.1, 0.3, COLOR = 'ORANGE', SURF_ID = 'LEAK', IOR = +1/

&VENT XB = 1.3, 1.7, 2.3, 2.7, 3.9, 3.9, COLOR = 'MAGENTA', ID = 'INLET VENT', SURF_ID = 'HVAC', IOR = -3/

&VENT XB = 4.3, 4.7, 2.3, 2.7, 3.9, 3.9, COLOR = 'BLUE', ID = 'OUTLET VENT', SURF_ID = 'HVAC', IOR = -3/

&HVAC TYPE_ID = 'NODE', ID = 'N7', DUCT_ID = 'D6', VENT_ID = 'INLET VENT'/

&HVAC TYPE_ID = 'NODE', ID = 'N6', DUCT_ID = 'D6','D5', XYZ=1.5,2.5,5/

&HVAC TYPE_ID = 'NODE', ID = 'N5', DUCT_ID = 'D4', AMBIENT=.TRUE., XYZ=1.5,2.5,5/

&HVAC TYPE_ID = 'NODE', ID = 'N4', DUCT_ID = 'D5','D4','D3', XYZ=1.5,2.5,5/

&HVAC TYPE_ID = 'NODE', ID = 'N3', DUCT_ID = 'D2', AMBIENT=.TRUE., XYZ=1.5,2.5,5/

&HVAC TYPE_ID = 'NODE', ID = 'N2', DUCT_ID = 'D3','D2', 'D1', XYZ= 1.5,2.5,5/

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&HVAC TYPE_ID = 'NODE', ID = 'N8', DUCT_ID = 'D8', VENT_ID = 'OUTLET VENT'/

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&HVAC TYPE_ID = 'NODE', ID = 'N10', DUCT_ID = 'D9','D10','D11', XYZ=4.5,2.5,5/

&HVAC TYPE_ID = 'NODE', ID = 'N11', DUCT_ID = 'D10', AMBIENT=.TRUE., XYZ=4.5,2.5,5/

&HVAC TYPE_ID = 'NODE', ID = 'N13', DUCT_ID = 'D12', AMBIENT=.TRUE., XYZ=4.5,2.5,5/

&HVAC TYPE_ID = 'NODE', ID = 'N12', DUCT_ID = 'D13','D12', 'D11', XYZ= 4.5,2.5,5/

&HVAC TYPE_ID = 'NODE', ID = 'N14', DUCT_ID = 'D13','D14', XYZ= 4.5,2.5,5/

&HVAC TYPE_ID = 'NODE', ID = 'N15', DUCT_ID = 'D14', AMBIENT= .TRUE., XYZ= 4.5,2.5,5/

&HVAC TYPE_ID = 'DUCT', ID = 'D6', NODE_ID = 'N6', 'N7', LOSS = 116.125, 116.125, ROUGHNESS = 0.00015, LENGTH =1, AREA = 0.16 /

&HVAC TYPE_ID = 'DUCT', ID = 'D5', NODE_ID = 'N4', 'N6', LOSS = 5.81, 5.81 , ROUGHNESS = 0.00015, LENGTH =1, AREA = 0.16 /

&HVAC TYPE_ID = 'DUCT', ID = 'D4', NODE_ID = 'N4', 'N5', LOSS = 2.4, 2.4, ROUGHNESS = 0.00015, LENGTH =1, AREA = 0.16 /

&HVAC TYPE_ID = 'DUCT', ID = 'D3', NODE_ID = 'N2', 'N4', LOSS = 0.2, 0.2, ROUGHNESS = 0.00015, LENGTH =1, AREA = 0.16 /

&HVAC TYPE_ID = 'DUCT', ID = 'D2', NODE_ID = 'N2', 'N3', LOSS = 1.88, 1.88, ROUGHNESS = 0.00015, LENGTH =1, AREA = 0.16 /

&HVAC TYPE_ID = 'DUCT', ID = 'D1', NODE_ID = 'N1', 'N2', REVERSE = .FALSE., LOSS = 1.55, 1.55, ROUGHNESS = 0.00015, LENGTH =1, AREA = 0.16,FAN_ID = 'FAN_IN'/

&HVAC TYPE_ID = 'DUCT', ID = 'D8', NODE_ID = 'N8', 'N9', LOSS = 155.78, 155.78, ROUGHNESS = 0.00015, LENGTH =1, AREA = 0.16 /

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&HVAC TYPE_ID = 'DUCT', ID = 'D10', NODE_ID = 'N11', 'N10', LOSS = 4.38, 4.38, ROUGHNESS = 0.00015, LENGTH =1, AREA = 0.16 /

&HVAC TYPE_ID = 'DUCT', ID = 'D11', NODE_ID = 'N10', 'N12', LOSS = 8.92, 8.92, ROUGHNESS = 0.00015, LENGTH =1, AREA = 0.16 /

&HVAC TYPE_ID = 'DUCT', ID = 'D12', NODE_ID = 'N13', 'N12', LOSS = 4.74, 4.74, ROUGHNESS = 0.00015, LENGTH =1, AREA = 0.16 /

&HVAC TYPE_ID = 'DUCT', ID = 'D13', NODE_ID = 'N12', 'N14', REVERSE = .FALSE., LOSS = 1.95, 1.95, ROUGHNESS = 0.00015, LENGTH =1, AREA = 0.16, FAN_ID = 'FAN_OUT'/

&HVAC TYPE_ID = 'DUCT', ID = 'D14', NODE_ID = 'N14', 'N15', LOSS = 0.06, 0.06, ROUGHNESS = 0.00015, LENGTH =1, AREA = 0.16 /

&HVAC ID='FAN_IN',TYPE_ID='FAN',VOLUME_FLOW = 5.965/

&HVAC ID='FAN_OUT',TYPE_ID='FAN',VOLUME_FLOW = 7.821/

&DEVC ID='Pressure_room_centre', XYZ= 3.0, 2.5, 3.7, QUANTITY='PRESSURE' /

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&SLCF PBY= 2.5, QUANTITY = 'VELOCITY', VECTOR=.TRUE./

&TAIL /
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