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Feasibility and Spontaneity of Jetfans for Aircraft Fire Safety

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Abstract
Fires have been a serious threat yet to be comprehensively addressed, in safe air transportation. The fire occurrence in cabin is well etched by the unpredictable fire behavior transiting to larger high potential fires. The work investigates feasibility of automated ventilation jetfan in the aircraft to minimize fire spreading and enhance control action time, thus reducing fire hazards. Present work proposes utilization of jetfan as a potential fire safety system in aircrafts. Aircraft cabin is simulated as an enclosure with fire. Varying fire sizes are designed and placed at various locations in the enclosure. The physical insight is drawn using heat feedback mechanism. Parametric simulations were carried out on the governing parameters like, HRRPUA (Heat release rate per unit area), volume flow, jet-fan size and location. The effectiveness of jet fan and optimum location for varying fires is thoroughly analyzed. The work is motivated by the need to have better fire safety for safer aviation programs.

Keywords: *Fire safety, jetfan, aircrafts, exhaust, heat release rate, FDS-SMV*

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INTRODUCTION

Air transport is the fastest and an integral mode of transport infrastructure. With significant technological advancement, air transportation has transformed the transference of passengers and cargo at regional, national and international scale and has become primary means of carrier traveling providing vital connectivity. Air travel primarily occurs in the form of helicopters, aircrafts and jets that can sustain flight and is an important enabler in achieving economic growth and development. However, on a global scale, the integration of air transport broadly incurs imperative issues of safety, security, environmental protection and sustainability in air. In the last few decades, air transportation operation has results in a significant increase in global fatal accident rate (Figure 1). For air transportation, as airliners and airlines increased over the turn of the century, so did aircraft accidents making it a potential source of irreplaceable loss of mankind, resources and property; every year huge amount of economic investment is made on the safety. Of diverse ways of aircraft accidents, the most prominent have been crashes primarily due to fires. It has been surveyed and reported that over 44% of deaths caused in aircraft crashes are due to fires (Figure 2).

It is estimated that aircraft fires cost the global airline industry well over 2 billion dollars. This remarkable figure is mainly because of the momentous damage caused by the aircraft operations resisting the imperative hazards. Aircraft fire in the air is one of the most hazardous situations that can be faced with. A fire on board an aircraft can lead to the catastrophic loss of the aircraft within a very short space of time (Figure 3). Once a fire has become established, it is unlikely to extinguish it.

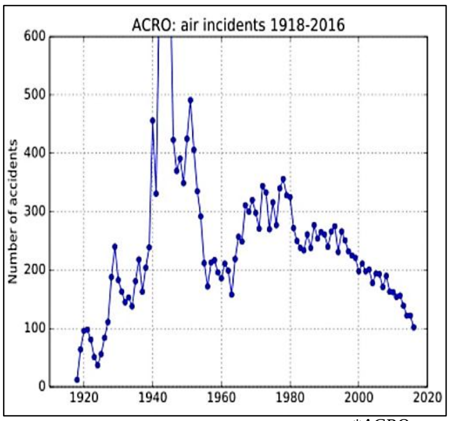

Fig. 1: *Air Accidents Data (*ACRO).*

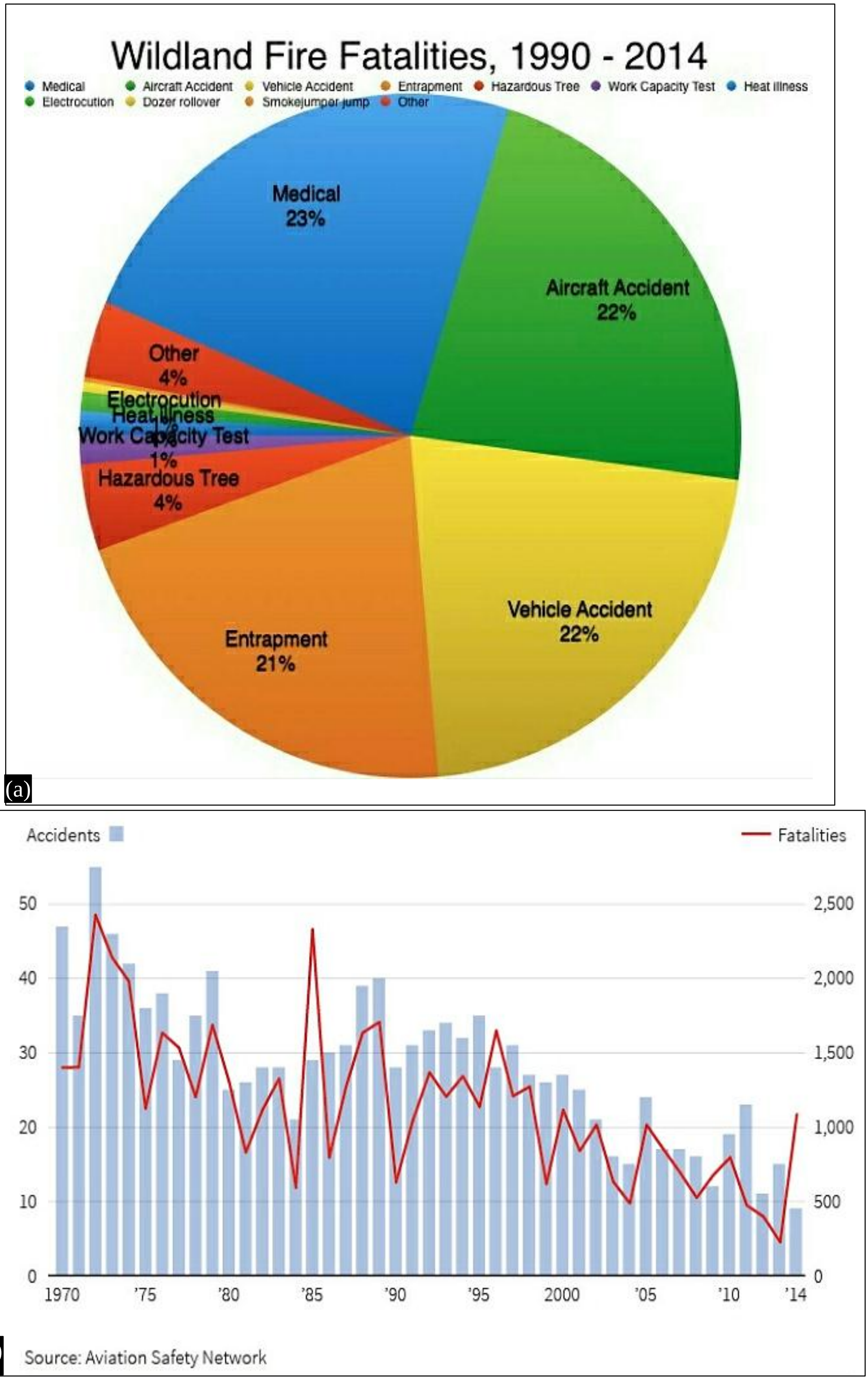

Fig. 2: *Data Highlighting:* ***(a)*** *Aircraft Fire Accidents Density and* ***(b)*** *Corresponding Fatality Rates.*

Fig. 3: (a–c) *Varied Fire Accident Modes.*
*(*National Geographic Pictures).*

A running aircraft has plenty of hot things that can quickly ignite a fire. Most of them are under the cowling, under conditions of a component failure because of age, fatigue, or improper maintenance. The cylinders absorb the heat and warm to a few hundred degrees which can be hot enough to ignite many combustibles. A crack in the exhaust system or a cylinder can ignite the spray from a broken fuel or oil line to create an impromptu blast furnace. Electrical power from alternators, generators, and batteries constitutes another potential heat source. With power routed to virtually every part of the aircraft for lighting, deicing, radios, landing gear and flap motors, and fuel pumps, the electrical system is another prime candidate for starting fires. Insulation, adhesives, fabrics and insulation on the wiring make great fuel that an errant electrical spark can ignite. Although the engine and electrical system constitute the primary ignition sources, they are not the only causes of fires. To fly an aircraft, one requires fuel, oil, and, often, hydraulics. Apart from the tendency to flow, these fluids have one more thing in common: they are all flammable. The fires in an aircraft can be classified as: Engine Fire, Cabin Fire and Hidden Fire.

- A hidden fire is the most dangerous type of fire owing to limited detectability and an ability to initiate abruptly forcing an emergency landing.
- Cabin fires include electrical fire (in-flight and ground fire involving an electrical malfunction), lavatory fire, waste container fire, overhead compartment fire, seat fire and passenger PED fire.
- Engine fire details to the technical errors and component malfunctions. These fires result in excessive heating which affect aircraft systems and ultimately affect the structural integrity of the aircraft leading to loss of control. The smoke and fumes from fires reduce visibility within the

aircraft. An electrical fire in an aircraft typically generates a lot of thick white smoke which can render the flight crew blind, unable to see the instruments or see out of the windows. Smoke and fumes from an in-flight fire are likely to be highly toxic and irritating to the eyes and respiratory system. Smoke and fumes may therefore quickly incapacitate the crew unless they take protective action.

For precaution, most of aircrafts use smoke detectors, portable fire extinguishers, automatic fire extinguishing systems, fire/crash axe/crowbar, fire protection gloves, smoke protection devices, smoke goggles and fire blankets. The primary step to fire safety depends upon fire detection. The detection of fires within the aircraft cabin usually depends on the ability of the flight crew member to see or smell smoke. Detecting the fire location is particularly difficult due to the air flow distribution within the aircraft. Furthermore, fires can start in inaccessible locations, making it difficult or impossible to extinguish the fire. The inability to access the source of the fire is a serious limitation that significantly reduces the likelihood of successfully extinguishing it. However, inspite of recent scientific and technological advancements, the complexity of the problem has prevented a complete understanding of the fire safety in aircrafts owing to conditional occurrence, unidentified locations, and insufficient fire controlling system. This has necessitated active research efforts to understand mechanisms controlling fire spread, the nature of aircraft fires, related implications, control and to predict the significant energy transfer because of temperature difference. Fire primarily comprises of three components (Figure 4) viz.:

a) Ample oxygen to support combustion.
b) Adequate fuel or combustible material.
c) Enough heat to reach the ignition temperature.

Fire spread commonly denotes to the fire propagating parallel to the surface; and the rate at which the flame spreads over the solid fuel is stated as the fire spread rate. A part of thermal energy released in the chemical reactions, heats up the fuel ahead known as heat feedback (Forward Heat Transfer). A stationary fire can be easily controlled, however, the main issue of aircraft fires emanates from the spreading of fires. The continuous fire spreading over combustible surfaces strengthens with time, making extinguishing difficult. The analysis of fires is carried out in the form of a small scaled fire as flame.

Spreading of fire is broadly classified as the concurrent flow (upward) and opposed flow/downward spread (Figure 5). In a concurrent flow spreading fire, the air moves in the same direction as the propagating fire. In opposed flow, the air moves opposite to the propagating fire and restricts the forward heat transfer. Thus, compared to the concurrent spreading fire, opposed spreading fires are slow steady and unperturbed to analyse.

An aircraft is a closed pressurized vessel and any leak in the same can turn hazardous within seconds. Aircraft fire propagation is controlled by the forward heat transfer and the resultant of hot combustion gases. Most of the aircraft fires are concurrent flow spreading fires and thus difficult to control and extinguish.

Fig. 4: *Schematic of Fire Components.*

Fig. 5: *Pictorial Views of Opposed and Concurrent Flame Spreads.*

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The occurrence of these fires on aircrafts is likely to have with hazardous effects and loss to human life, property, resources and damages aircraft beyond repair, challenging fire safety on air-ports and in operating space and huge financial investment being drawn into fire prevention every year. One of the persisting issues is that it is impossible to eliminate all ignition sources. With fires emanating by engine failure, short circuits or mechanical failure, involuntarily result in uncontrolled damage and are impossible to extinguish. Although appreciable work had been done, the complexity has prevented a complete understanding.

An imperative aspect of aircraft fire spreading is the hot exhaust in an enclosed/confined area. In such circumstances, unless the exhaust smoke can be cleared, it is very difficult to control the aircraft. The available solutions to the problem are not complex, however, the use of a specific technique, understanding and implementation of the same demands for a specialized knowledge. One of the solutions that have not been worked upon is fast and effective removal of hot exhaust using an efficient ventilation system. Present work explores the feasibility and spontaneity of jetfans as an efficient fire safety tool. A jetfan is essentially a fan configuration which largely ingests in the polluted air and diverts it to a specific manifold. They are primarily used as an exhaust and pollution control systems for fast evacuation of toxins and pollutants. Jetfan utilization details from early 1960 and have been proven effective in car parking and tunnels. The operation involves easy installation, usage, cost effective and covers minimum space (Figure 6).

For aircrafts, jetfans are likely to be very effective in fast removal of hot toxic exhaust gases, minimizing the forward heat transfer. Reduced forward heat transfer minimizes fire spreading which in turn increases the control time for the necessary actions for evacuation procedures, thus minimizing the damage. Following the classical work of Halada *et al.* on the reconstruction of the forest fire propagation case when people were entraped by fire, appreciable experimentation, computational, theoretical, analytical work had been carried out to denote [1]. The reviews can be found in literature which provides a commending base for systematic fire analysis [2–10]. With recent scientific advancement, the work base for investigation of fire spreading have gravitated to the utilization of computational resources as experiments are difficult to perform to gain physical insight into the mechanism. Glasa *et al.* worked upon the mathematical foundations of elliptical forest fire spread model [2]. The noticeable work was closely followed by Halada *et al.* on the computer forest fire simulation as a tool for fire progress prediction and back analysis of fire origin [3]. Weisenpacher *et al.* carried out the computer simulation of automobile engine compartment fire to gain noteworthy physical insight into the fire impact [6], which was followed by the parallel model of FDS used for a tunnel fire simulation [9]. Recently, Halada *et al.* studied computer modelling of automobile fires to study the fire spreading as close as possible to the real conditions [10].

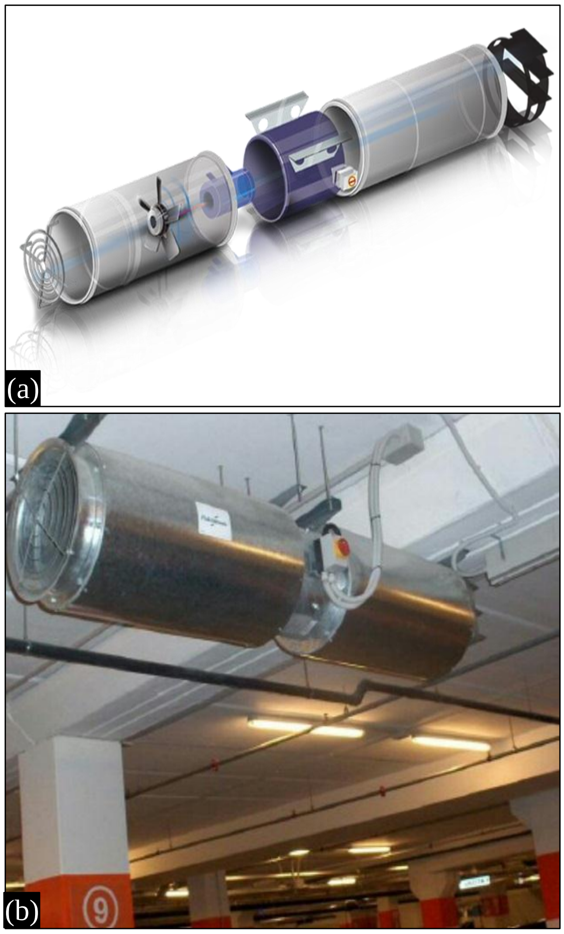

Fig. 6: *Pictorial Views of **(a)** Jetfan **(b)** with Installation.*

In the light to above mentioned works, to extinguish aircraft fires, it is necessary to understand the behavior of fire propagation. The specific objectives of the study are:

a) To investigate the implication of magnetic field on flame spread rates.
b) To examine the role of key controlling parameters.

The work is motivated by the need of better aircraft fire safety for:

i. Smooth aircraft operations.
ii. To ensure passenger safety.
iii. Losses and hazards prevention.

NUMERICAL SIMULATIONS AND SOLUTION METHODOLOGY

The work is carried out computationally with simulations performed on fire dynamics simulator (FDS)-smoke view (SMV) which is a computational fluid dynamics (CFD) model of pre-driven fluid flow. Numerical calculations are carried by fire dynamics simulator (FDS), a large eddy simulation (LES) computational fluid dynamics (CFD) model of low speed fire-driven fluid flow. FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. Smoke-view (SMV) visualizes smoke and fire attributes realistically by displaying tracer particle flow, shaded contours of gas flow data such as temperature and flow vectors showing flow direction and magnitude in each plane (at each grid node) determined from soot densities computed by FDS (Figure 7). Fire dynamics simulator (FDS) is a computational fluid dynamics code developed to calculate fire-driven flows both in enclosures and in the ambient. The governing equations are discretized in space and time. Time differencing takes the form of a second order, explicit predictor-corrector method. Spatial differences, taken on a uniform computational grid, are either second order, central differences or upwind differences depending on the parameter and the local CFL number. The verification and validation of the model are well discussed in the FDS verification and validation guides [5].

An enclosure (10 m×4 m×4 m) was selected as a prototype to aircraft cabin for the numerical experimentation (Figure 8). The testing fire was designed using heat release rate per unit area (HRRPUA). The jetfan (1 m×0.2 m×0.4 m) was placed at the center of the enclosure (varied for optimized cases). Inner walls of the fan are at 0.2 m from the outer walls from all sides.

The base conditions selected were HRRPUA=1000 kW/m^2, volume flow=0.8 kg/s with mesh size=50, 20, 20. The simulations were carried out for 1200 sec. It is important to note that the results presented represent repeatability of the third order for all the readings.

RESULTS AND DISCUSSION

The parametric numerical simulations were carried out for varying HRRPUA, volume flow rate, varying enclosure size for effective jetfan location and varying mesh size. Prior to the main simulations, validation of the software prediction was carried out on a benchmark conventional case of enclosure fire.

Numerical predictions were thoroughly validated by comparing the results with benchmark experimental data using standard ASME-E-1385 (Figure 9). The results matched reasonably well, thus fulfilling the requirements for a simulation program and expected to offer good physical insight. Furthermore, a mesh independence study was carried out to finetune the predictions. Two different mesh sizes were used to predict the jetfan effect. Figure 10 shows the effect of varying mesh size for the base case and the finer mesh. It was noted that the finer mesh under predicts results than the base case. The fluctuations in heat feedback in the finer mesh were limited. Subsequently, simulations were carried out with the base mesh.

First, a study was carried out to evaluate the effectiveness of jetfans. HRRPUA was varied systematically for the cases of 1000, 2500, 5000 kW/m^2 respectively. Figure 11 shows the effect on the enclosure. Looking at the plot, one can note that the HRRPUA follows a monotonic trend with the time. The heat feedback is significantly reduced owing to the presence of jetfan. It was observed that the intensity of the fires and consequential heat feedback rates varied drastically. Larger fires result in immense heat feedback as compared to the smaller fires in an enclosure. The variation of designed HRRPUA from 1000 to 2500 kW/m^2 yields 150% increase in heat feedback, whereas, from 2500 to 5000 kW/m^2 yields 100% increase in heat feedback. The plot also recovers that smaller fires represent better controllability with followed steadiness, whereas larger fires largely represent unsteady characteristics.

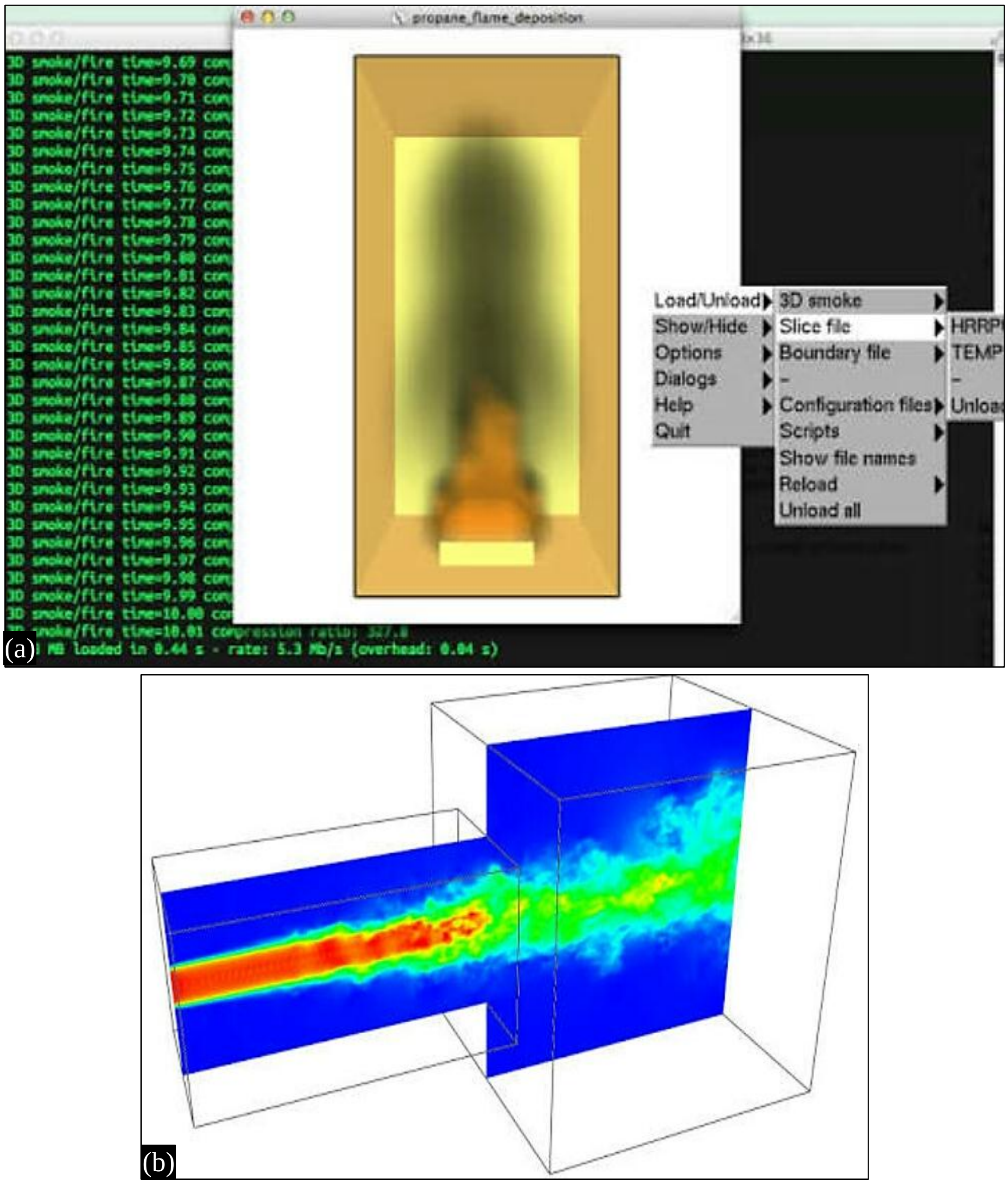

*Fig. 7: Pictorial Depiction of FDS-SMV Simulations **(a, b)**.*

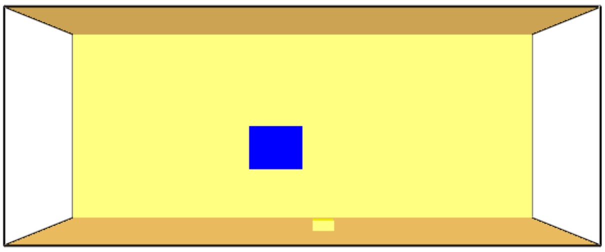

***Fig. 8:** Prototype Aircraft Cabin Enclosure.*

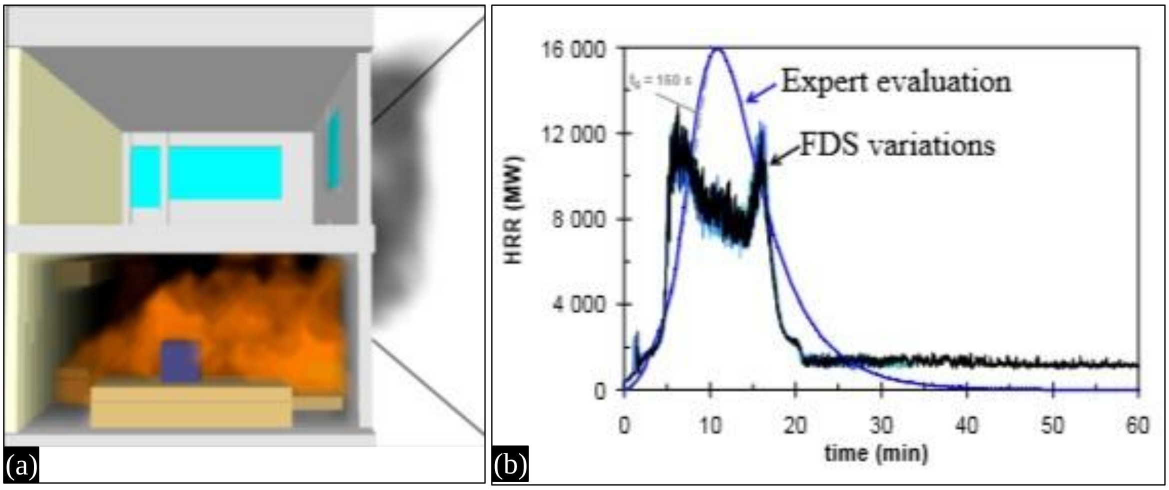

Fig. 9: *Validation Study* ***(a)*** *Enclosure with Fire,* ***(b)*** *Prediction Comparison.*

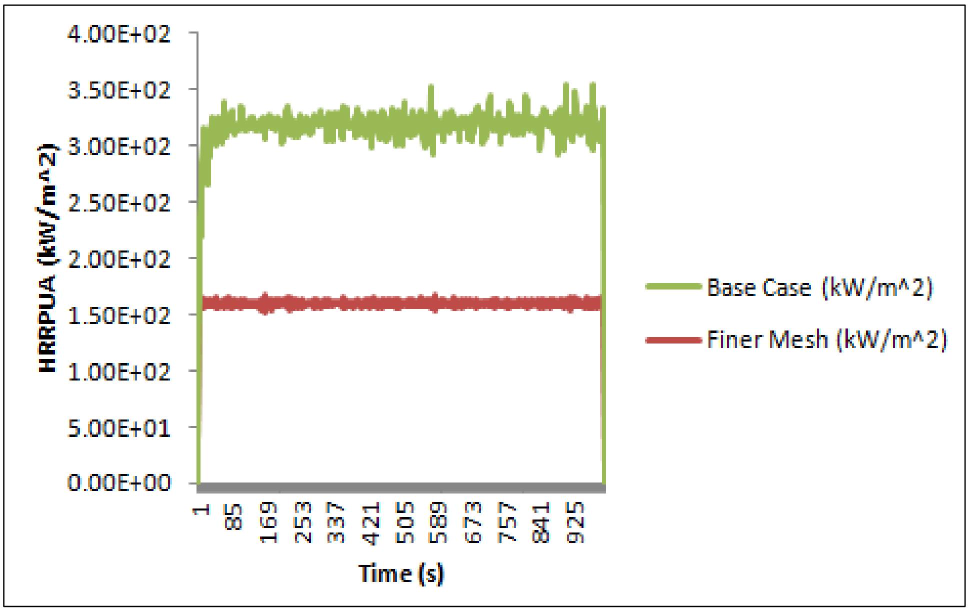

Fig. 10: *Variation of Mesh Size on Heat Feedback and Jetfan Effect.*

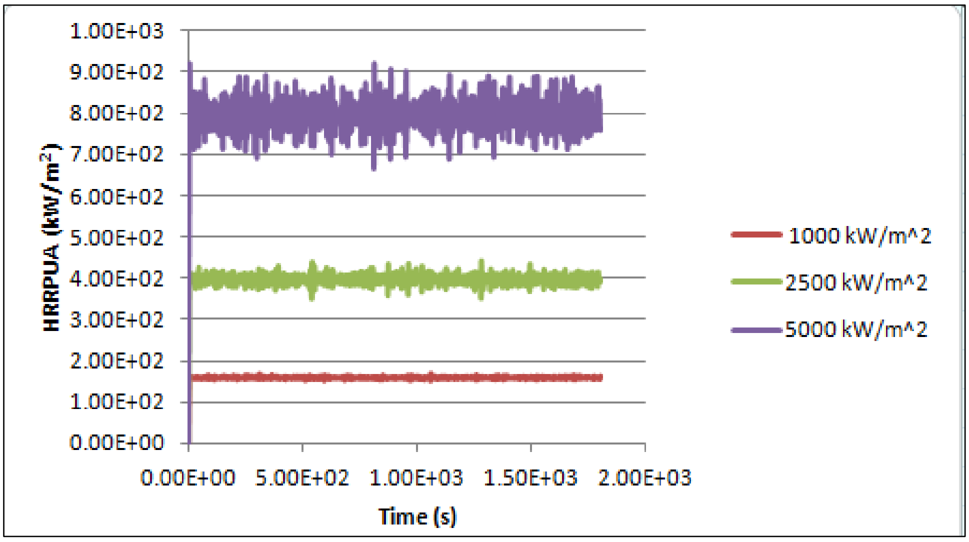

Fig. 11: *Variation of Heat Feedback of Designed HRRPUA Fires with Time.*

The significant drop in heat feedback of the designed larger fires strongly advocates the effectiveness of the jetfans in removing hot exhaust gases. Figure 12 shows the enclosure fire representation for the cases of 1000 and 5000 kW/m^2 fires in an enclosure. To understand the operational mechanism, next we look at the simulated flow and thermal contours of the designed enclosure fires at different times.

Looking at the contours in Figure 13, one can note that the maximum temperature of exhaust plume for 1000 kW/m^2 is 220°C, whereas for larger fire 5000 kW/m^2 rises to 520°C. The capacity of hot exhaust plume to preheat the surrounding combustible increases with bigger fires as can be seen from Figure 13. The presence of high temperature zones around the jetfans confirms the jetfan action of removing hot exhaust gases by directing them into manifold. The thermal flow field in the enclosure with respective designed fires is shown in Figure 14, where the contours show the generation of high temperature zones and consequential recirculation zones.

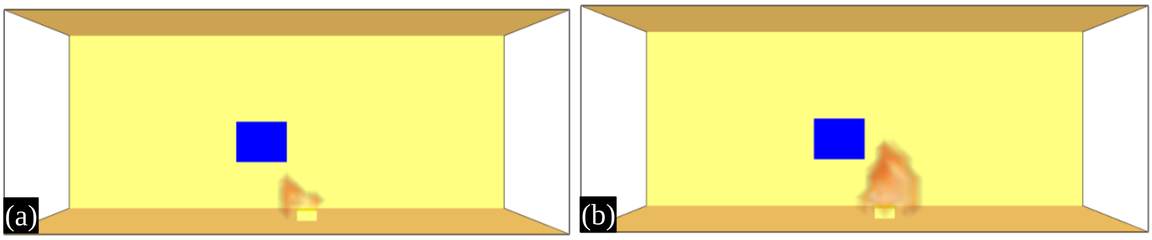

Fig. 12: *Enclosure Fire Setup for the Cases of **(a)** 1000 kW/m^2 and **(b)** 5000 kW/m^2.*

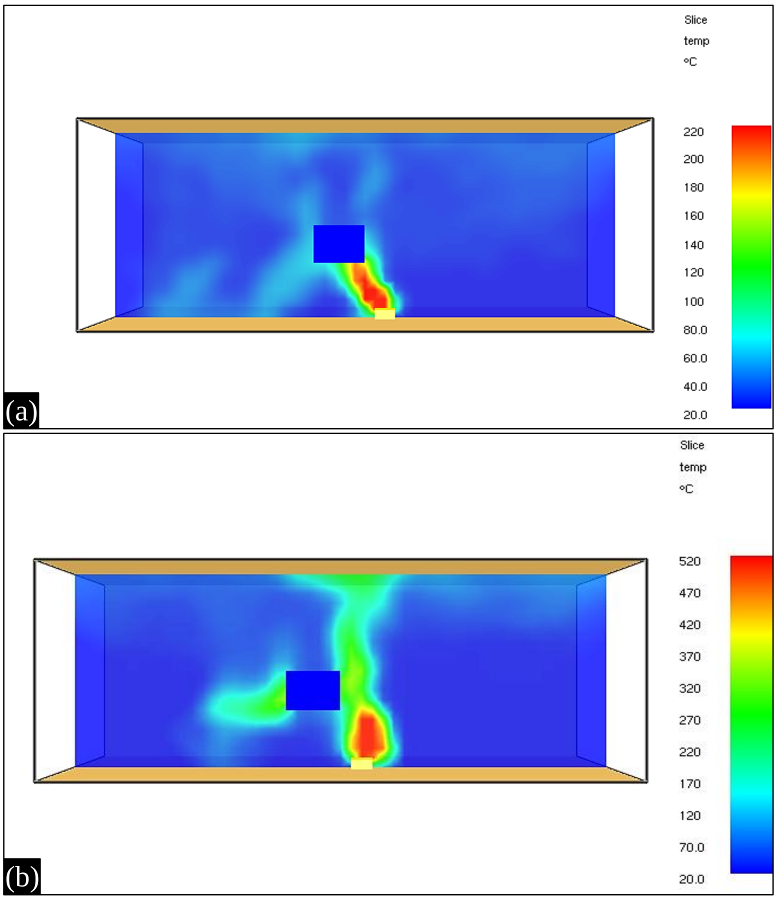

Fig. 13: *Temperature Contours at 100 sec for Enclosure Fire Setup for the Cases of **(a)** 1000 kW/m^2 and **(b)** 5000 kW/m^2.*

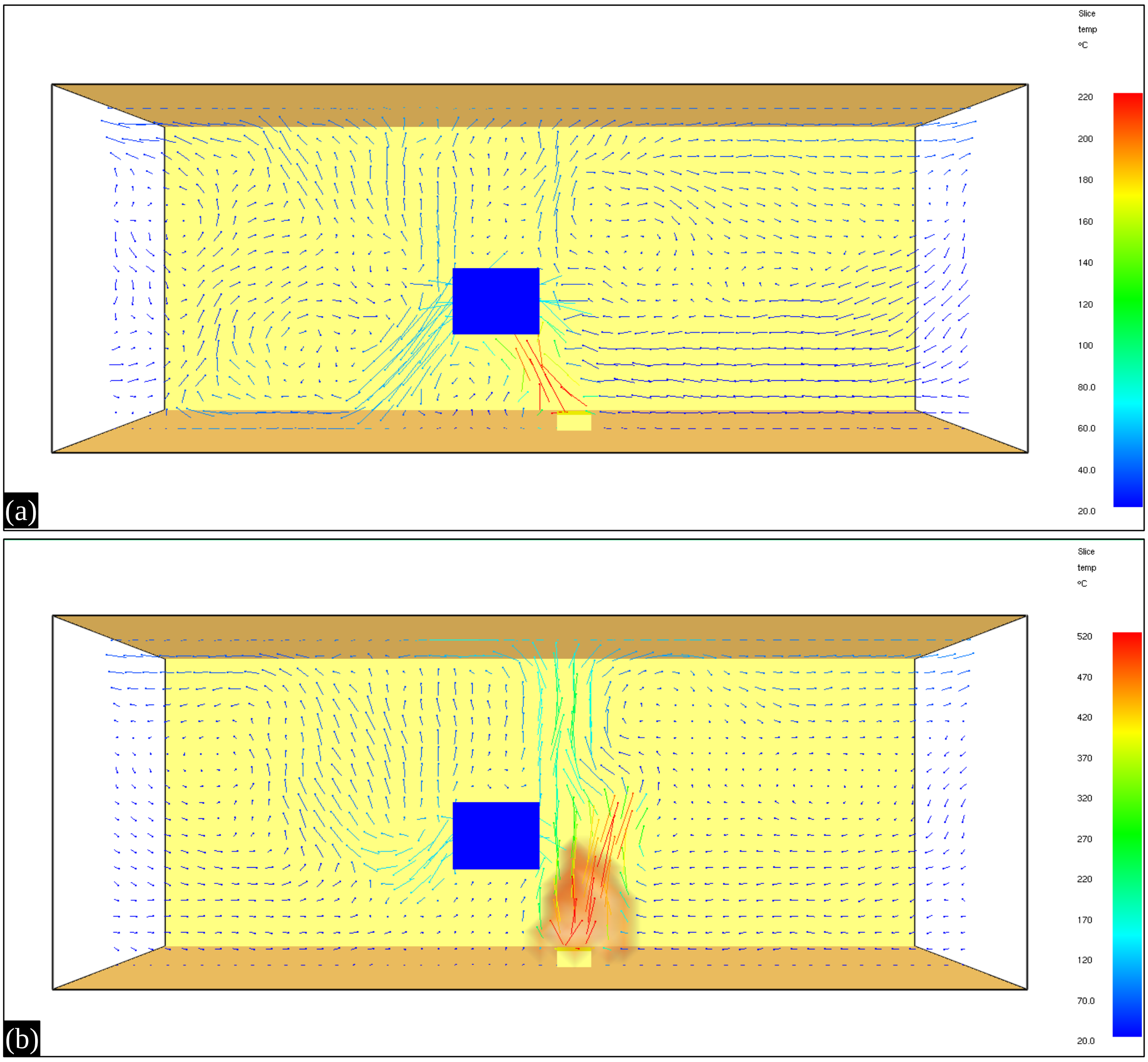

Fig. 14: *Flow Field Contours at 100 sec for Enclosure Fire Setup for the Cases of* ***(a)*** *1000 kW/m^2 and* ***(b)*** *5000 kW/m^2.*

Owing to the stronger buoyant convection in larger fires, the plume can be noted to be drawn faster towards the enclosure top surface and presence of stronger jet action reduces recirculation zone intensity and more preheated air is being drawn in to the manifold. Whereas, the presence of increased recirculation zones in the smaller fires indicates the sufficient high temperature flow being ingested and small temperature gradient flow residual. The intensity of the flow direction can be observed using the directional velocity distribution.

Figures 15 and 16 show the directional velocity contours for the cases of the smaller fire (1000 kW/m^2) and larger fire (5000 kW/m^2). Looking at the contours, one can note that the directional velocity changes are higher for larger fire than the smaller fires. The maximum velocities for smaller fires in subsequent directions varies as ‘u=1.05 m/s’, ‘v=0.80 m/s’ and ‘w=1.60 m/s’ and minimum as ‘u=–2.45 m/s’, ‘v=–0.70 m/s’ and ‘w=–1.90 m/s’. Whereas, for larger fire, ‘u=1.50 m/s’, ‘v=0.70 m/s’ and ‘w =5.55 m/s’ and minimum being ‘u=–2.50 m/s’, ‘v=–0.80 m/s’ and ‘w=–1.45 m/s’. It is important to note that the negative velocity represents altered flow direction. The flow velocity range varies significantly for both the cases in all directions; however, the higher effect was noted to occur in ‘u’ and ‘w’ directions. The contours depict zones of stronger recirculation zones. Higher gradient values indicate better jetfan action with substantial exhaust flow being ingested preventing excessive preheating of the enclosure causing easier spread.

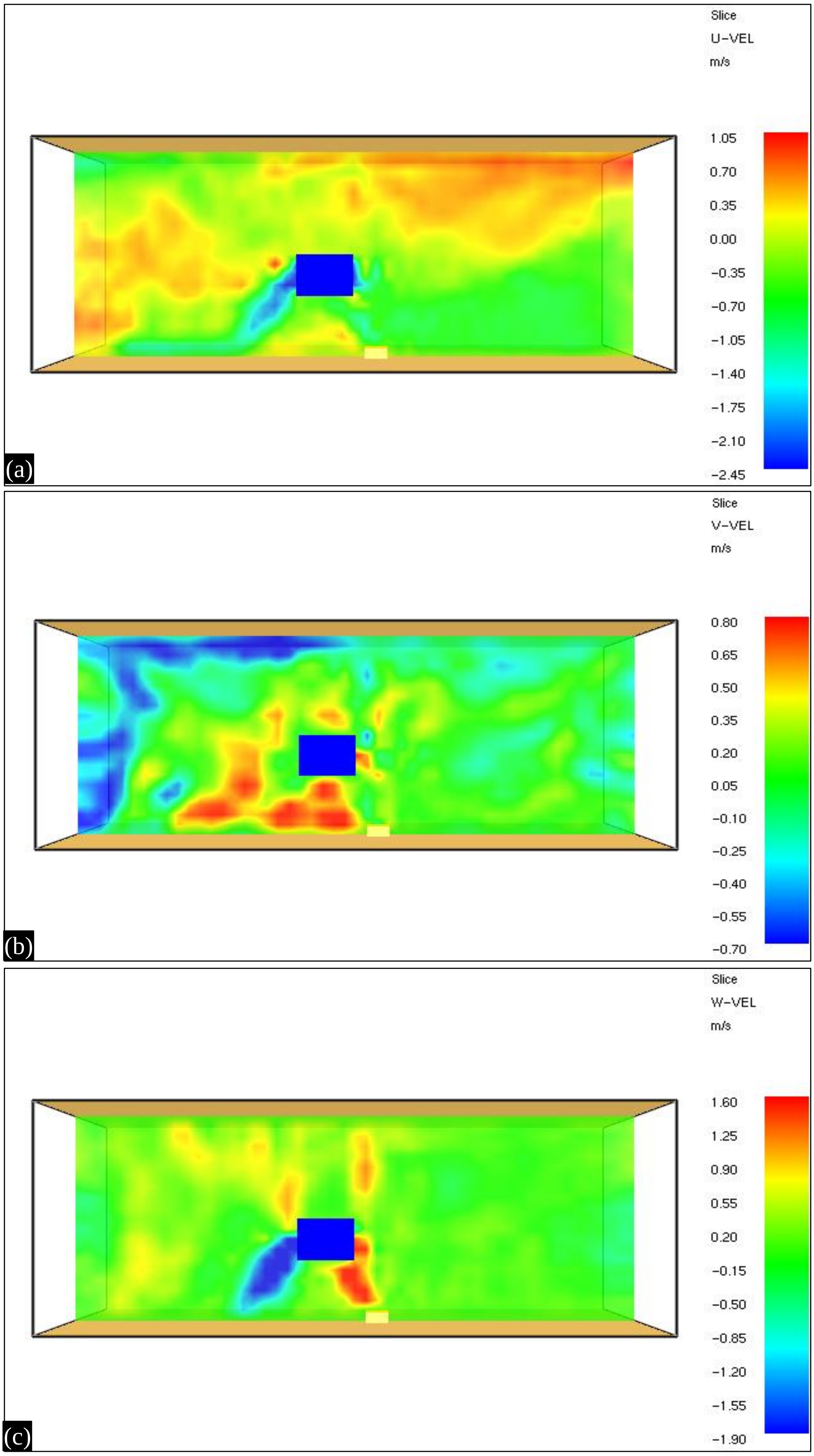

***Fig. 15:** Directional Velocity Field Contours at 100 sec for Enclosure Fire Setup for the Cases of 1000 kW/m^2 **(a)** 'u' **(b)** 'v' and **(c)** 'w'.*

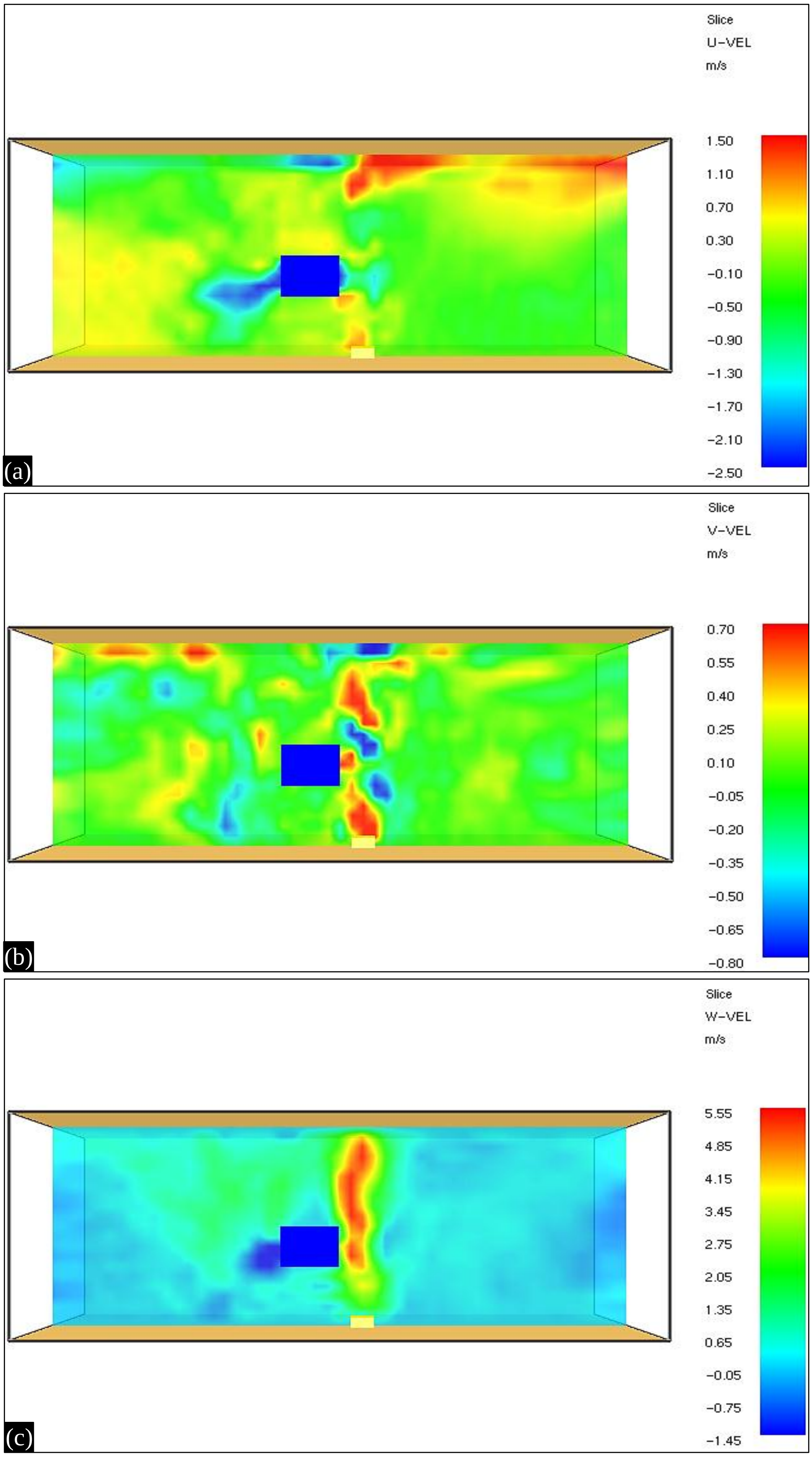

Fig. 16: *Directional Velocity Field Contours at 100 sec for Enclosure Fire Setup for the Cases of 5000 kW/m^2* ***(a)*** *'u'* ***(b)*** *'v' and* ***(c)*** *'w'.*

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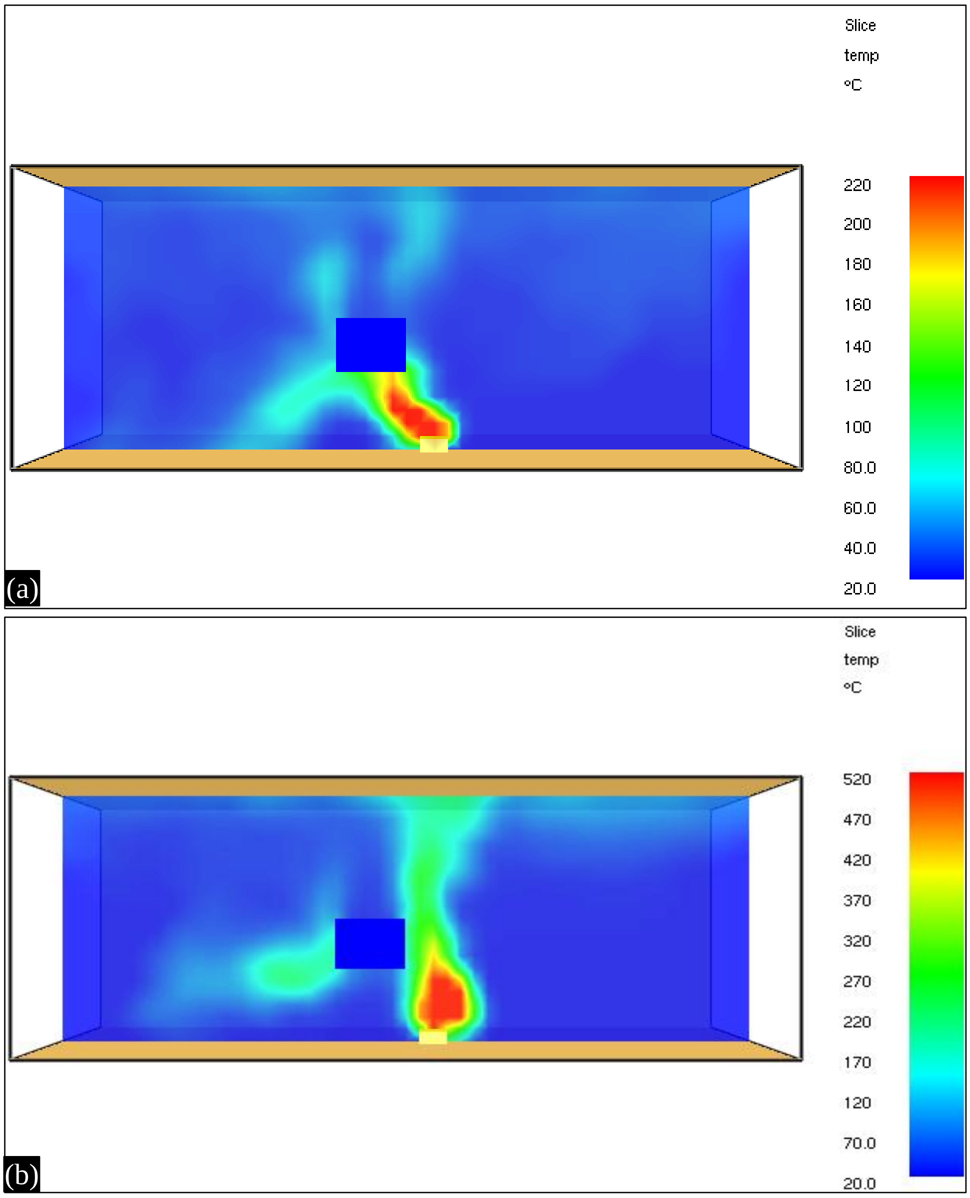

Fig. 17: *Temperature Contours at 1000 sec for Enclosure Fire Setup for the Cases of **(a)** 1000 kW/m^2 and **(b)** 5000 kW/m^2.*

As the phenomenon is largely time dependent, the jetfan action for the above-mentioned cases was observed after 1000 sec. Figures 17 and 18 show the thermal and flow field contours for the above-mentioned cases after 1000 sec. Looking at the plots, one can note that the effectiveness of jetfan action sustains. Figures 19 and 20 show the directional velocity contours after 1000 sec for afore-mentioned cases.

The directional velocity contours corroborate with the thermal and flow-field contours for effectiveness of jetfan as potential exhaust removal system for aircrafts. The continued stability of the jetfan action with time reassures of the reliability of utilization. With the effectiveness of jetfan action being established, next, a study was carried out to understand the effect of jetfan operating under varied condition of volume flow. It is important to note that in the present study within an enclosure, exhaust flow density is being considered as a factor and standard mass flow rate is stated as the volume flow. The base case of HRRPUA=1000 kW/m^2, enclosure fire with volume flow of 0.80 kg/s was selected. The simulations were carried out for two diverse cases of volume flows of 0.20 and 1 kg/s respectively (Figure 21). The cases represent conditions of reduced volume flow and elevated volume flow conditions. The heat feedback conditions were found to be limited to the base case conditions with the jetfan action. The result implies that jetfan action in an enclosure for a fixed fire with varying volume flow is likely to remain unaltered.

This signifies that as a ventilation system, the jetfans are expected to handle diverse conditions of effective exhaust plume removal.

Another important aspect to cross-verify jetfan feasibility is, operation under varying enclosure conditions or adaptability to different cover conditions. For this study, the enclosure size was reduced by two units (half) and four units (one-fourth) of the base case. The base case conditions of HRRPUA=1000 kW/m^2 and volume flow of 0.80 kg/s were maintained. Figure 22 shows the variation of heat feedback using jetfan action with varying enclosure size.

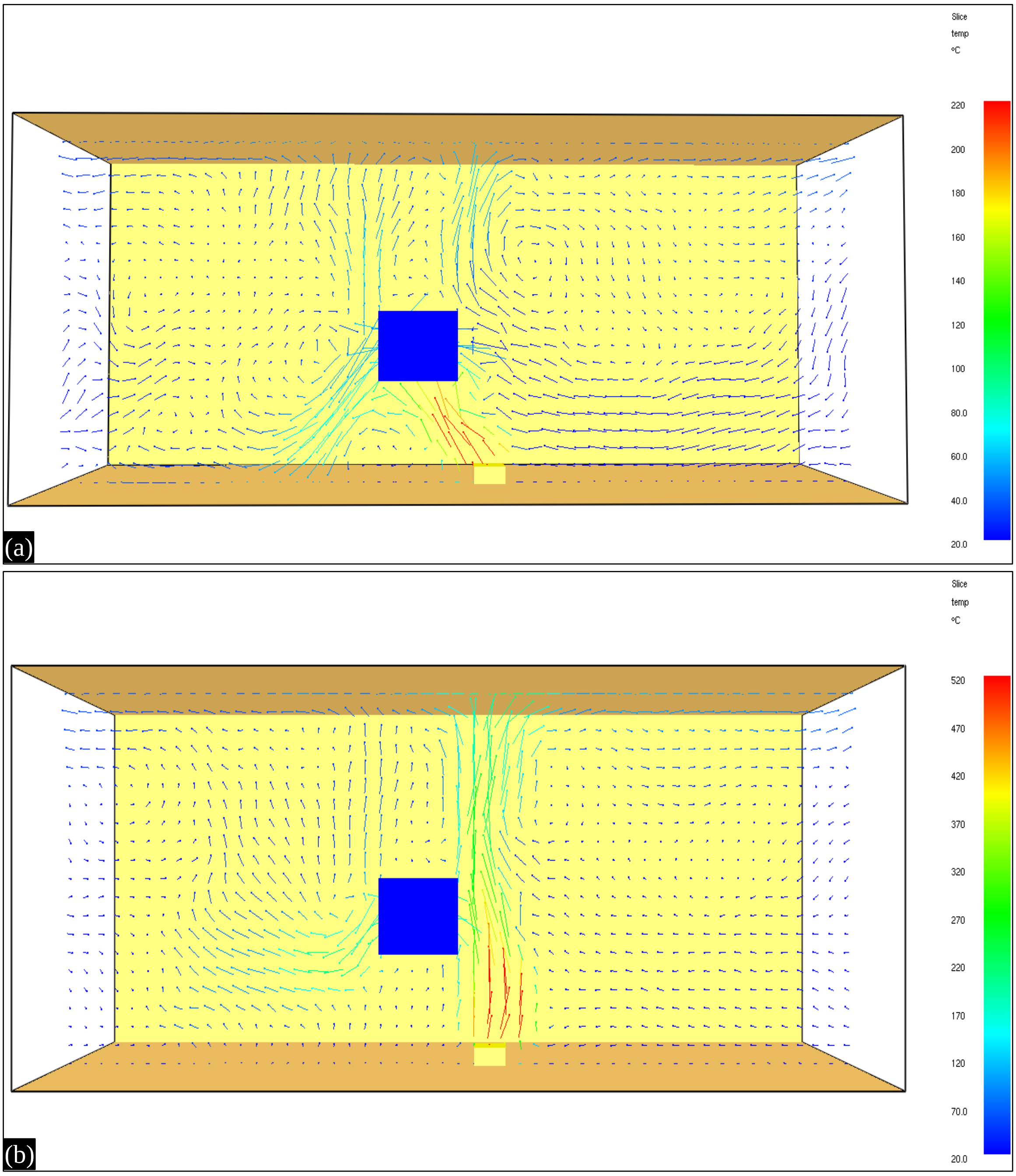

Fig. 18: *Flow Field (Vector) Contours at 1000 sec for Enclosure Fire Setup for the Cases of* ***(a)*** *1000 kW/m^2 and* ***(b)*** *5000 kW/m^2.*

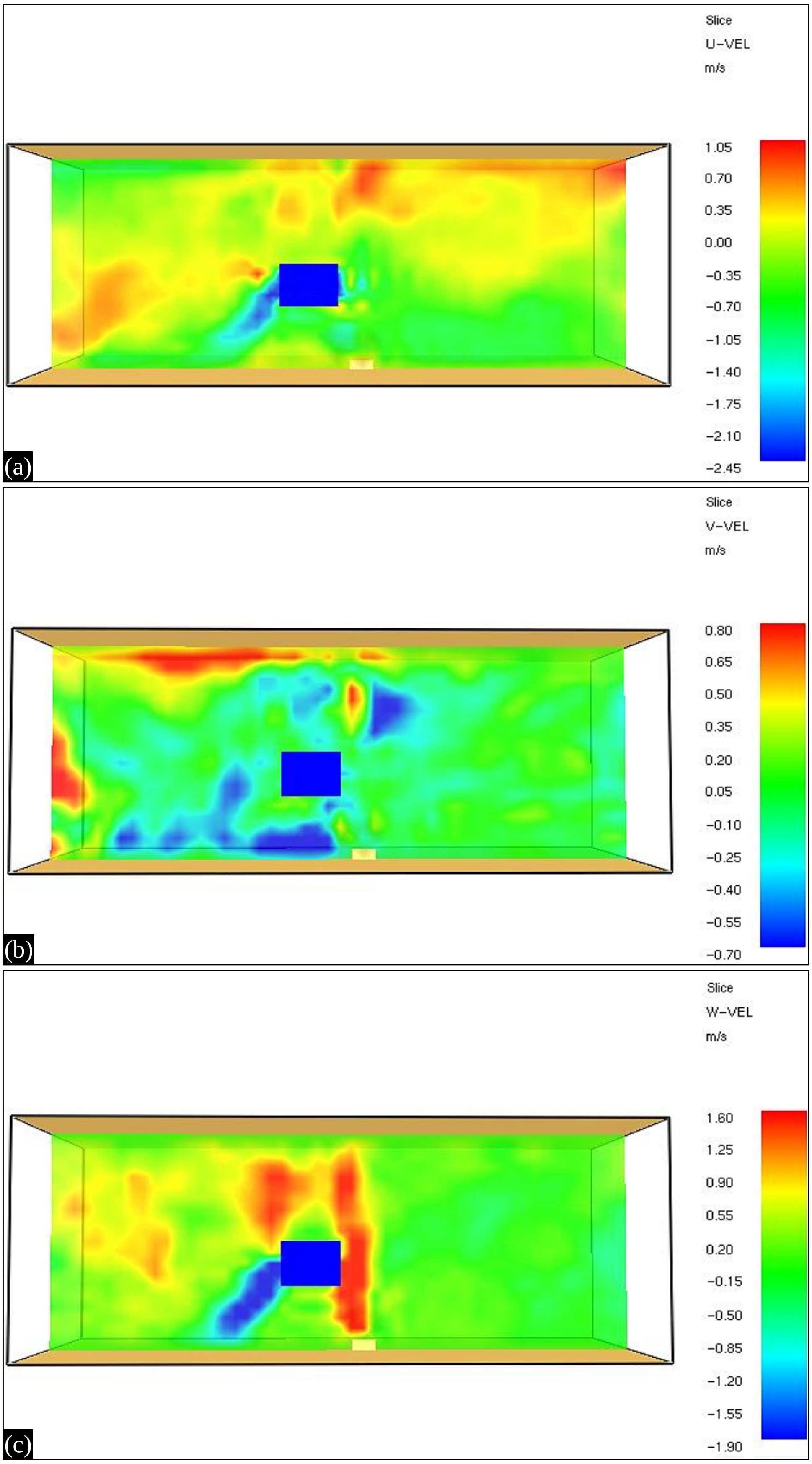

Fig. 19: *Directional Velocity Field Contours at 1000 sec for Enclosure Fire Setup for the Cases of 1000 kW/m^2* ***(a)*** *'u'* ***(b)*** *'v' and* ***(c)*** *'w'.*

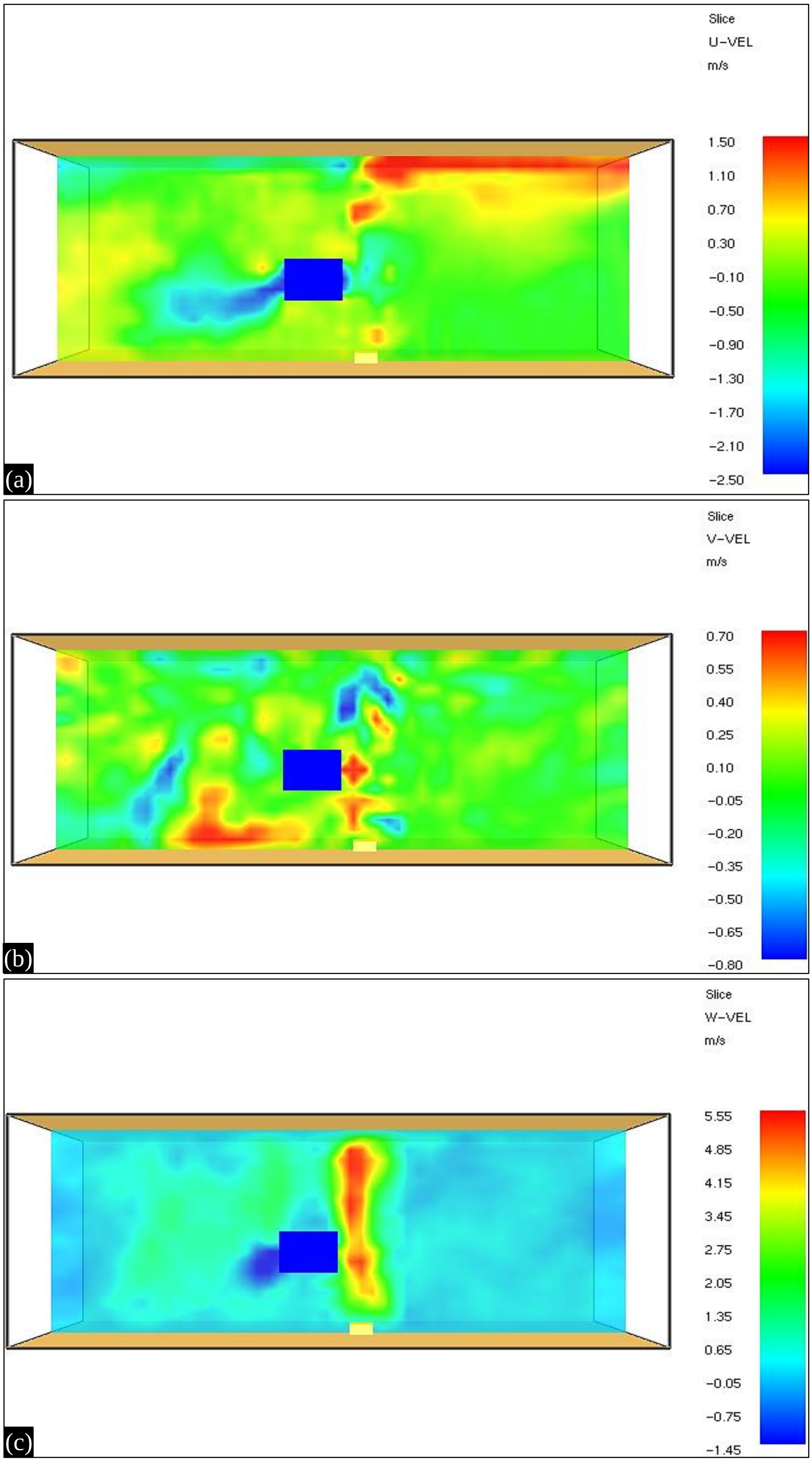

Fig. 20: *Directional Velocity Field Contours at 1000 sec for Enclosure Fire Setup for the Cases of 5000 kW/m*^{2} ***(a)*** *'u'* ***(b)*** *'v' and* ***(c)*** *'w'.*

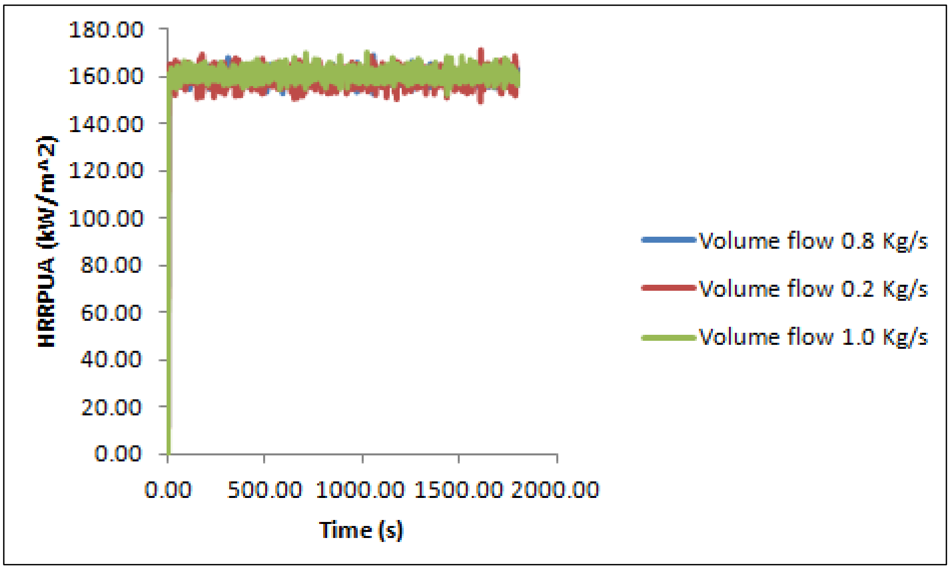

Fig. 21: *Variation of Heat Feedback with Volume Flow.*

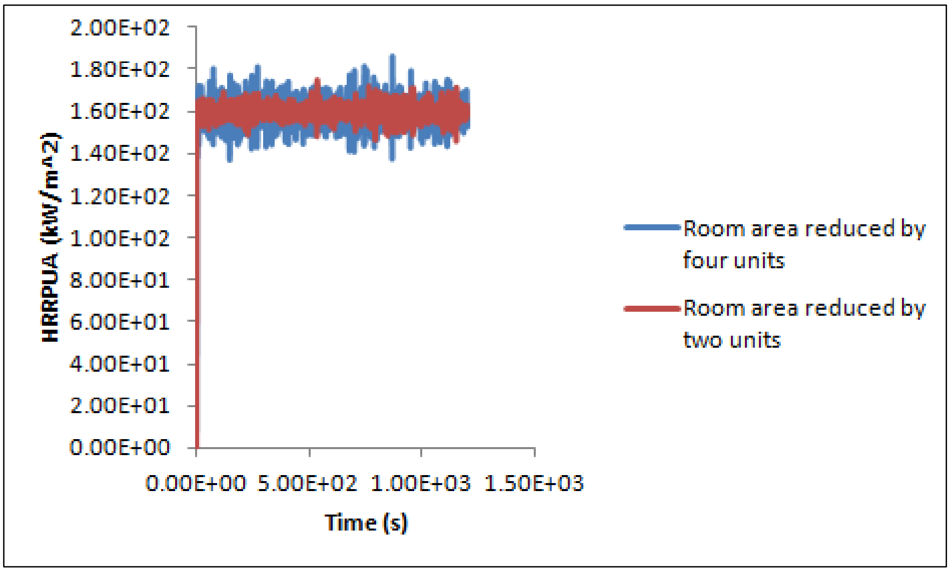

Fig. 22: *Variation of Heat Feedback with Enclosure Size.*

Looking at the plot, one can note that the spontaneity of jetfan action persists under varying enclosure conditions. The resultant heat feedback is predicted reasonably well within base case predictions. The result states that as a thermal system, the jetfan action is unresponsive, when operated under varying enclosure conditions. For an aircraft, under varying conditions of fires exhaust plume, under varying cabin size and varying volume flow conditions, the jet fan performance as a potential exhaust ventilation system is not affected. This adds to the fact that, it removes toxic and hot exhaust plume effectively under varying conditions, thus preventing lives, resources, spreading of fire owing to excessive preheating. Thus it ensures smooth aircraft operations and passenger safety with minimization of losses and hazards.

CONCLUSIONS

Occurrence of fire in cabin during any condition is likely to result in the severely hot and toxic gases preheating the enclosed space for fire spreading and posing serious health hazards. This necessitates the high temperature smoke to be extracted quickly. Appreciable safety work had been done; however, the conventional duct systems are insufficient to prevent loss/damage apart from occupying sufficient space and often cross other services. Present work numerically investigates the feasibility and spontaneity of jetfans for aircraft fire protection. An enclosure with varying fire sizes and jetfan are designed and systematic simulations were carried out on controlling parameters viz., HRRPUA (Heat release rate per unit area), volume flow and enclosure size. The software predictions were well compared with the experimental data and matched reasonably well. Results show that jetfan are comparatively efficient to reduce heat feedback from varying sized fire intensities thus enhancing control action and minimizing losses. The predictions are supported by the related flow and thermal analysis. Jetfan were noted to work efficiently under varying conditions of volume flow and enclosure size.

Application of the Work

The work is motivated by the need to have better fire safety for aviation programs. The results are well validated and thus can be very insightful/useful in controlling the real-world terrestrial and extra-terrestrial fires on aircrafts and enclosed vehicles structures.

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