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Transient characteristic of the flow of heat and mass in a fire as the basis for optimized solution for smoke exhaust

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ABSTRACT

Smoke and Heat Exhaust Ventilation Systems (SHEVS) are technical solutions used to limit the consequences of a fire in a building, related to the spread of the smoke. Currently, the design methodologies follow an assumption, that if a system constantly exhausts amount of the smoke estimated with a calculation method based on an onerous steady-state fire scenario, the building should be safe. This paper introduces a different approach to optimal system design, based on the transient characteristic of the fire. The main idea is that a system can adapt to the momentary density of the removed smoke, to benefit from the thermal expansion of gases in the fire. As the fire grows, the temperature does rise, and the pressure within installation falls down, and so do the forces acting on ducts, dampers and other elements. This behaviour is observed in high-temperature furnace tests of exhaust fans, during which the change of pressure and power-supply requirement in changing temperature can be measured. The author presents results of 9 high-temperature tests that are a proof of the concept. The practical implementation of the idea presented in this paper could mean, that a system designed with an existing methodology for ambient conditions, could work with a higher capacity in high-temperature, without additional strain on the elements of the system. This shift in thinking allows using higher capacity systems, in place of currently used, by artificially limiting the capacity of an oversized fan in ambient conditions and increasing it, following the measurements of the temperature of the exhausted air or pressure in the shafts. Beside the theoretical introduction to a new concept, the paper presents results of 8 numerical analysis (CFD) of airflow in an enclosed car park during a fire, performed in ANSYS® Fluent® solver. The author created an User Defined Function (UDF) to automate the transient change of the fan boundary condition, dependant on the exhausted smoke temperature – following the assumptions of the adaptive solution presented in the paper. Four CFD analysis were performed for each traditional and new solution, and their results were compared in with qualitative and quantitative approach. Results of the CFD analysis show a possible gain of 25–41% of system capacity, using the same ductwork and reaching the same design goal, as contemporary SHEVS. The pressure within the ductwork and at fans is almost constant in the adaptive analysis. The paper is closed with a discussion of legal aspects, possible limitations in the design and the further research necessary to establish the new method of the design.

1. Introduction

1.1. General overview

Smoke produced in a fire is the greatest threat to the users of a building. It is produced quickly, in vast amounts. It can travel a great distance, to surprise unsuspecting occupants, intoxicate, incapacitate and be the direct cause of fatalities. To limit this threat, engineers design various technical solutions under a common name of "*smoke control systems.*"

This paper serves as an introduction to a new concept in smoke control – dynamic, transient adaptation of Smoke and Heat Exhaust System (SHEVS), employing the natural phenomenon of thermal expansion of heated air to increase the efficiency of existing systems. The phenomenon of thermal expansion of air and smoke in fire is well known, and used in Fire Safety Engineering in the design of longitudinal ventilation systems in tunnels [1,2], car parks [3], atria [4] or mechanical supply to stairwells [5]. The thermal effects will also drive the performance of natural ventilation systems, especially in adverse wind conditions [6,7]. The thermal effects are also included in the procedure for high-temperature testing of exhaust fans [8].

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In Section 1 author presents the traditional approach to the development of SHEVS in a broad field of view, including the architectural design, makeup air management, and also mechanical design of the system; Section 2 presents the transient changes of the flow of mass and heat in a fire, and the results of 8 full scale furnace tests of fans; tion 3 serves as an introduction to the new, adaptive concept; Section 4 presents a CFD study that illustrates the differences between traditional and adaptive approach in form of a case study with Computational Fluid Dynamics (CFD); Section 5 is dedicated to the discussion of possible limitations and further research ideas.

1.2. Smoke control systems

Klote [9] following NFPA 92 [10] defines a smoke control system as "*an engineered system that includes all methods that can be used singly or in combination to modify smoke movement.*" A subdivision may be done based on the physical mechanism of how the smoke control is achieved: (1) compartmentation, (2) dilution, (3) pressurization, (4) airflow and (5) buoyancy. This paper is dedicated to mechanical SHEVS, often referred to as venting systems [11]. These systems utilize mechanical exhaust ventilators to remove smoke from a reservoir bounded by walls and draft curtains, and supply ventilators that simultaneously provide makeup air into ventilated compartment. To put this solution in the classification of Klote, the physical phenomena behind them are a combination of (4) and (5), and sometimes (2). In a performance-based design approach (PBD) the goal of such systems is to provide a safe environment for evacuation, defined through tenability criteria. In this case, the SHEVS systems are often referred as tenability systems.

SHEVS are widely used in a range of buildings – large volume malls, atria, convention centers, sports arenas and warehouses [12]. Similar solutions, although different in their design assumptions, may be found in enclosed car-parks, corridors, offices, shops and even tunnels. Illustration of basic components of SHEVS is shown in Fig. 1.

An SHEVS is designed for a given architecture and occupancy of a building – either newly designed or existing. The architectural boundaries can be considered as the first limitation of conception, and together with the local law they will determine the type of a system to be used, and sometimes its basic performance requirements. This preliminary choice is often performed by laymen who are not smoke control engineers nor Fire Safety Engineers and do not have a deep knowledge of venting nor fire phenomena [13]. There are numerous sources of knowledge related to SHEVS design. The main sources are smoke control handbook [14], essays [9,12] and various standards on the design of such systems, to name a few most popular:

- NFPA 92 and 204 [10,11];
- BS 7346-4 [3];
- VDI 6019-1 [15];
- DIN 18232 [16];
- CEN/TR 12101-5 [17].

All of the guidelines presented above share the same philosophy of the design, that follows a simple workflow scheme: (i) choice of a design fire, (ii) estimation of the amount of smoke released in the protected volume and (iii) estimation of required parameters of the system to cope with the threat. The basic parameters that describe a system are the mass flow of air (smoke) to be exhausted, the temperature of the smoke, number and location of exhaust points, air supply strategy, the scenario of operation and cooperation with other safety features of the building, etc.

In the past, a variety of tools was used to determine the performance of SHEVS, including hand calculation models, zone models [18] or scale modelling [19]. Today, the common approach is to use Computational Fluid Dynamics (CFD) tools to estimate the performance of the system, against tenability criteria [20,21], based on the Available and Required Safe Evacuation Time concept (ASET/RSET, [22,23]). The tenability criteria within the building are expressed as a function of time, and compared to the transient analysis of occupant evacuation.

1.3. Air supply

For a properly working system, it is not only necessary to remove sufficient amount of the hot smoke, but also replace this air with makeup air and not cause mixing of the layers (cold and hot). The air must be supplied through large openings at low velocity [24,25]. Air supplied at a height or with too high velocity will mix with the smoke, eventually leading to smoke lodging of the building with a cold smoke.

The air supply inlets may be mechanical or natural. The first ones will usually have constant flow rate, and will provide the same mass/volume, despite the conditions in the building caused by the fire. The natural supply points will supply a flow of mass, that in a simplified way can be considered as the difference between mass removed from an airtight building, and provided by the mechanical means.

In some types of smoke control systems the opposing flow of incoming air is meant to have an active effect on the smoke layer, and push it away (longitudinal ventilation in tunnels, jet-fan systems in car parks, etc.). In this case, the air flow has a minimal required velocity, referred to as the critical velocity, that prevents backlayering of the smoke [1,26].

2. Transient high temperature effects on smoke management

2.1. Change of flows and performance in a real fire

Fire is an emotional event – a theater of a flame, heat, air and smoke, rapidly changing in a transient motion. We are still unable to predict this phenomenon with a pure, mathematical description, although we can estimate the effects of a prescribed fire on the environment inside of the building and an exhaust system. In the design process the fire is quantified through a concept of a design fire – a probable fire scenario that can be considered representative from a risk assessment point of view. The choice of the design fire will essentially drive the design of smoke control system. The design fire can be either a steady state scenario, with a constant maximum rate of heat release (HRR), or a transient scenario with prescribed change of heat release, following results of an experiment or a historical fire. Steady-state scenarios are usually used in the system design with hand calculations, and the transient scenarios mostly in the CFD verification of the system design. The changes of the environment in the building, following a transient fire scenario, are shown in Fig. 2. The change of dry air density with temperature is shown in Fig. 3.

The fire itself may be described as a release of heat and mass into a system, that changes as the fire grows or decays (Fig. 2, chart (a)). The size of the fire (the rate of heat release, HRR) will determine how much smoke is generated, and how much air entrains the convective plume – which essentially means that the amount of smoke that enters the reservoir will follow the growth and decay of the fire (b). As the HRR increases, the temperature of the smoke generated within the compartment will increase as well (c), and that will lead to the drop of the density of smoke. This change of density is a key feature of the performance of smoke and heat