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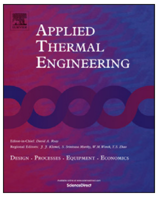

Adiabatic surface temperature as thermal/structural parameter in fire modeling: Thermal analysis for different wall conductivities

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HIGHLIGHTS

- The new useful concept of "adiabatic surface temperature" (AST) is investigated.
- The effect of wall thermal conductivity and of convective heat transfer coefficient on the use of AST is analyzed.
- The AST use is right for properly evaluated convective heat transfer coefficient.

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ABSTRACT

The new useful concept of "Adiabatic Surface Temperature" or more commonly known as AST, introduced by Wickström et al. in 2007, is investigated in this study. Adiabatic surface temperature can be used for bridging the gap between fire models and temperature models; for example, it offers the opportunity to transfer both thermal information of the gas and the net heat flux to the solid phase model, obtained by CFD analysis.

In this study two numerical analyses are carried out in order to evaluate the effect of wall thermal conductivity and of convective heat transfer coefficient on the adiabatic surface temperature as thermal/structural parameter in fire modeling. First one CFD analysis simulating a fire scenario, "*conjugate heat transfer*", with a square beam exposed to hot surface, is carried out to calculate AST, convective heat transfer coefficient and temperature field in the beam. In the second one, a conductive analysis is carried out on "*standalone beam*" imposing a third type boundary condition on its boundaries assuming the AST, evaluated in the conjugate analysis, as external temperature. Different convective heat transfer coefficients are imposed on the beam walls; the beam is of concrete or steel. Results are presented in terms of net heat flux on beam surfaces, convective heat transfer coefficients and temperature profiles on the beam walls, temperature fields for the two, CFD and conductive, analyses and the relative temperature and net heat flux percent errors. Results underline that convective heat transfer coefficient profiles and adiabatic surface temperatures on the bottom and lateral beam walls are independent of the wall thermal conductivity value, whereas the net heat flux values increase as wall thermal conductivity increases, fixed the emissivity.

1. Introduction

The built environment is evolving rapidly. Modern buildings are increasingly designed to be energy efficient, with sustainability considerations and structural optimization making structures lighter and leaner than ever before. Novel construction techniques and the use of innovative building materials and systems are resulting in the design of highly unconventional building shapes and sizes [1]. The growing complexity of the architectural designs introduces more fire risks. For this reason, a good understanding of the development in compartment fires is necessary for fire researchers and firefighters in the prediction and the estimate of temperature and smoke production.

Fire Safety Engineering (FSE) is defined as the application of engineering principles based on the knowledge of human behavior and on the scientific understanding of the phenomena of fire and its effects, to save life, to protect property and to preserve the environment and the heritage. Following the World Trade Center disaster, a number of authoritative organizations, such as FEMA [2] and ISE [3] have identified joint integrity as a key to maintain structural integrity in fire and have called for extensive research on joints under fire conditions. Yet, despite recent progresses in

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understanding how steel structures behave in fire, large gaps still exist in understanding structural element behavior in fire.

In literature, the temperature of members exposed to fire is usually determined by first modeling the fire phenomenon by an empirical correlation or advanced computer simulation to obtain a temperature–time curve that represents the fire environment, then substituting the fire curve into a 1D condensed heat transfer model to obtain the structure temperatures [4]. Pope and Bailey [5] present a comparison of two parametric fire modeling techniques and one field model against large-scale post-flashover test data, providing useful quantitative data on three techniques concerning fire modeling. The finite element method based on thermal/structural models (FEM models in the following) typically assumes a global gas temperature enveloping a fairly detailed model of a beam or column, in order to predict the behavior of structural elements in fire. CFD models and FEM analysis have been used to define the thermal fluxes on fire exposed surfaces and the resulting temperature distribution in the structures of interest [6].

Conjugate CFD and structural analyses would be the best way to analyze the thermo-structural problem, since the fire evolution and the structural response are interconnected. However, the large computational resources required due to the different time and space scales necessary for the discretization of thermo fluid-dynamic and structural problems make, nowadays, this approach impracticable. Alternatively to the conjugate approach, thermo fluid-dynamic and structural problems could be solved separately, by using appropriate boundary conditions to couple the two models [7]. We can distinguish two main methodologies: “one way”, in which only the data collected by a CFD code are transferred to the structural code, and “two-way” where even the data produced by a FEM code are returned to the fire model. The latter method is more accurate but requires more computational time. Within this approach, Noordijk et al. [8] have developed a complete interface between the VESTA™ CFD code and the Diana™ FEM code, but this approach requires large computational time due to the double transfer of data.

The “one-way” approach, which allows to reduce the computational time, could be used preferably when the dimensions of the structural elements and their displacements due to structure deformations are negligible compared to the size of the compartment. In this case it is possible to assume that the deformations of the elements due to thermal loads do not affect appreciably the evolution of the hot gases.

The exchange of information between the CFD and FEM codes is one of the open problems in FSE. It greatly influences both the accuracy of the solutions and the computational time. The European Community has funded a study on the different methods of coupling the two codes and on the data exchange format, called FIRESTRUC [9]. Within this project, four different pairs of software CFD-FEM coupling have been compared ((JASMINE/SAFIR, VESTA/DIANA, FDS/ANSYS and JASMINE/STELA) with six different types of data exchange, providing indications for their use.

Franssen [10] performed a study on the “one-way” methodology, that compared data obtained through CFD-FEM analysis by using two types of algorithms for exchange parameters: the former proposed by Watson and Philip [11], called “natural neighbors” and the second, proposed by themselves, based on trilinear interpolation of thermal parameters in the nodal points where the fluid dynamics and structural discretizations overlap. Ren et al. [12] developed a dynamic transfer to share data between FDS and ANSYS codes.

A different approach was followed by Wickström that introduces the new useful concept of “Adiabatic Surface Temperature” or more commonly known as AST [13–15]. AST can be used for bridging the gap between fire models and temperature models, as well as between fire testing and temperature models. Wickström presents examples concerning how the concept of AST can be used in practice both in reaction-to-fire tests and in large scale scenarios where structures are exposed to high and inhomogeneous temperature conditions [16]. Moreover, Byström et al. [17] carried out a full-scale compartment fire experiment with wood crib fuel in a concrete building. Temperatures were measured with plate thermometers and ordinary thermocouples. These two different temperature devices recorded different temperatures, especially near the floor surface. The adiabatic surface temperature was derived by a heat balance analysis from the plate thermometer measurements. In addition, the fire experiment scenario was also simulated with fire dynamics simulator. The fire source was specified as a given heat release rate, which was calculated from the measured mass loss rate of the wood fuel. The adiabatic surface temperatures at these measuring positions were simulated by the fire dynamics simulator model and compared with the experimental adiabatic surface temperatures. The comparative results showed that fire dynamics simulator predicted the adiabatic surface temperature accurately during the steady-state period.

Andreozzi et al. [18] evaluated the effect of beam wall emissivity and of convective heat transfer coefficient on the use of AST as thermal/structural parameter in fire modeling. Two, CFD and conductive, analyses were carried out in order to evaluate the effect of emissivity and of convective heat transfer coefficient to determine the AST; first one simulated a fire scenario, “*conjugate heat transfer*”, with a square steel beam exposed to hot surface and it was carried out to calculate AST, convective heat transfer coefficient and temperature field in the beam whereas in the second one a conductive analysis was carried out on “*standalone beam*”, imposing a third type boundary condition on its boundaries assuming the AST, evaluated in the conjugate analysis, as external temperature. Results were carried out for two different steel emissivity values and for standalone beam case three different convective heat transfer coefficients were used. Results showed that, for the lowest analyzed emissivity value (0.5), the adiabatic surface temperature was close to the gas temperature due to the reduction of the radiative heat flux component on the overall heat transfer. Moreover the heat flux values predicted by the standalone beam analysis reproduced quite faithfully heat fluxes obtained for the conjugate heat transfer model by imposing the convective heat transfer coefficient obtained by means of this latter model.

In this paper the authors investigate the effect of wall thermal conductivity and of convective heat transfer coefficient on the adiabatic surface temperature as thermal/structural parameter in fire modeling, using the same approach employed in Ref. [18]. Different convective heat transfer coefficients are imposed on the beam walls; the beam is of concrete or steel. Results are presented in terms of net heat flux on beam surfaces, convective heat transfer coefficients and temperature profiles on the beam walls, temperature fields for the two, CFD and conductive, analyses and the relative temperature and net heat flux percent errors.

2. Adiabatic surface temperature

In the following the adiabatic surface temperature, T_{AST}, definition proposed by Wickström [15–17] will be introduced, using a simplified radiative model. It has to be noted that the fire model does not need any assumption in computing radiation heat flux and convective heat transfer coefficient; the equation is the description of the adiabatic surface temperature, but it does not imply any particular way to the fire model to calculate heat flux.

In fire scenario, thermal exposure of solids can be considered as the sum of convective and radiative heat fluxes: