Applied Thermal Engineering 51 (2013) 573–585

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Influence of wall emissivity and convective heat transfer coefficient on the adiabatic surface temperature as thermal/structural parameter in fire modeling

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HIGHLIGHTS

► An open problem is to transfer parameters obtained by thermal to structural models.
► The useful concept of "Adiabatic Surface Temperature" (AST) is investigated.
► The AST use is right for properly evaluated convective heat transfer coefficient.

ARTICLE INFO

Article history:
Received 22 April 2012
Accepted 16 September 2012
Available online 25 September 2012

Keywords:
Adiabatic surface temperature
CFD analysis
Thermal/structural parameter
Fire safety

ABSTRACT

In fire engineering analysis, one of the open problem is the transfer of thermal parameters obtained by fire CFD model to FEM models for structural analysis. In this study the new useful concept of "Adiabatic Surface Temperature" or more commonly known as AST, introduced by Wickström, is investigated. The adiabatic surface temperature 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 CFD analyses are carried out in order to evaluate the effect of emissivity and of convective heat transfer coefficient to determine the AST. First one CFD analysis simulating a fire scenario, "*conjugate heat transfer*", with a square steel beam exposed to hot surface is carried out to calculate AST, heat convective coefficient and temperature field in the beam. 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 heat convective coefficients are imposed on the beam walls. The comparison between results obtained by means of the two proposed analyses shows the use of AST as transfer thermal parameter between CFD (Computational Fluid Dynamic) and FEM (Finite Element Method) models is appropriate when the convective heat transfer coefficient is properly evaluated.

1. Introduction

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 [1] and ISE [2] 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 understanding how steel structures behave in fire, large gaps still exist in understanding structural element behavior in fire.

Modeling fire spread in a building is a factor of a fire thermal/structural analysis used for fire safety designs of buildings. The effects of fires in buildings are object of fire precautions required by national regulations and codes of practice [3].

In the fire resistance of steel structures evaluations, the temperature of structural element (i.e. beams, columns or joint) to fire is the most important and critical parameter, and should be determined with agreeable accuracy [4,5]. In literature, the temperature of steel 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

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1359-4311/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2012.09.024

curve that represents the fire environment, then substituting the fire curve into a 1D condensed heat transfer model to obtain the steel temperatures [6]. Cadorin et al. [7,8] used the computer Ozone code, one-zone models for post flashover fires and two-zone models for pre-flashover fires, to describe a compartment fire model. In the successive years the fire modeling techniques have progressed rapidly and sophisticated CFD models (e.g. Fire Dynamic Simulator) have been developed to model the fire behavior. Pope et al. [9] 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; Betta et al. [10,11] show the CFD analysis results in terms of thermal fields on tunnel ceil in case of fire. The necessity to adopt CFD models is also due to the complexity of the real fire behavior and of full scale experiments, which depends on a lot of factors, such as temperature, smoke, carbon monoxide, carbon dioxide fire load (amount and distribution), combustion, ventilation, compartment size and geometry, such as active fire detection and suppression systems (smoke detector and sprinkler) and thermal properties of compartment boundaries. For example, Sun et al. [12], investigate, numerically and experimentally, the smoke movement in stairwell induced by a fire in an adjacent compartment showing the agreement between the FDS results and experimental data; Yang et al. [13] concentrate their research on the front velocity of the transient ceiling jet in corridor fires, comparing experimental/numerical correlations; Santangelo and Tartarini [14] realize an experimental approach within a real-scale facility against severe fire scenario.

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 [15], and have been used to evaluate the thermal field for fire resistance of concrete slabs reinforced with FRP bars [16].

The better interaction between the fire model and thermal analysis would be resolved within the same CFD software, through an approach known as "conjugate heat transfer", but the disadvantage of this approach is that it increases the complexity of the resulting system of equations. Alternatively, it is possible to operate with two

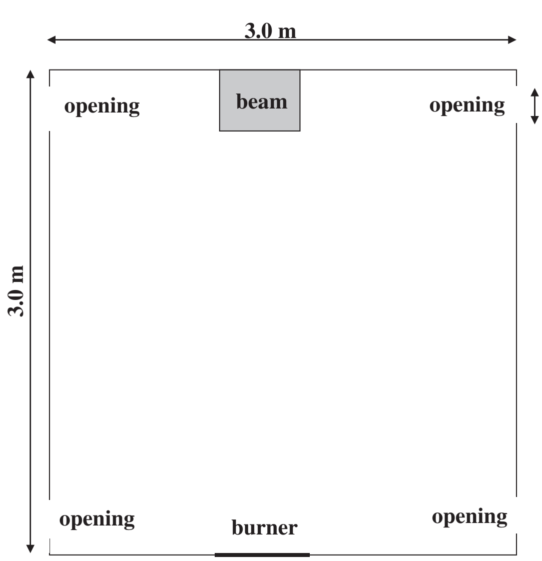

Fig. 1. Sketch of the first analyzed geometry.

Table 1
Air temperature properties.

Air thermophysical properties	
ρ	1.225 kg/m^3
c_p	1006.43 kJ/kgK
k_f	0.0242 W/mK
μ	1.79 10^{-5} Pa s

separate systems, CFD for the development of the fire and FEM for structure thermal analysis, that can exchange information as boundary conditions [17]. It is possible to distinguish two main methodologies: "one way" in which only the data collected by CFD code are transferred to the solid phase, or "two-ways" where even the data produced by FEM analysis model are returned to the fire model. The second method is more accurate but requires more computational time. Therefore, the problem is to identify a numeric parameter that can be easily used as interface between CFD calculation codes used to assess the development of the fire and those for FEM, which provide the thermo-mechanical response of the structure. A different approach was followed by Wickström that introduces the new useful concept of "Adiabatic Surface Temperature" or more commonly known as AST [18–20]. 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 [21]. Moreover, Byström et al. [22] show that the CFD analysis predicted the adiabatic surface temperature accurately during the steady-state period, comparing numerical and experimental results.

The adiabatic surface temperature offers the opportunity to transfer both thermal information of the gas and the net heat flux, obtained by CFD analysis, to the solid phase model.

In this study two analyses are carried out in order to evaluate the effect of beam wall emissivity and of convective heat transfer coefficient on the use of AST as thermal/structural parameter in fire modeling. First one CFD analysis simulating a fire scenario, "*conjugate heat transfer*", with a square steel beam exposed to hot surface is carried out to calculate T_{AST}, heat convective coefficient and temperature field in the beam. Second one 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 heat convective coefficients are imposed on the beam walls.

The results are presented in terms of convective heat transfer coefficients and temperature profiles on the beam walls both for the "*conjugate heat transfer*" and "*standalone beam*" analyses. Temperature fields are also presented for the two analyses. Relative percent errors between results obtained by means of conjugate case and the standalone beam case are provided. The comparison between results obtained by means of the two proposed analyses shows the use of AST as transfer thermal parameter between CFD and FEM models is appropriate when the convective heat transfer coefficient is properly evaluated.

2. Adiabatic surface temperature

In the following the surface adiabatic temperature T_{AST} definition proposed by Wickström [18–20] will introduced, using

Table 2
Steel thermophysical properties.

Steel thermophysical properties	
ρ	8030 kg/m^3
c_p	502.48 kJ/kgK
k_s	16.27 W/mK