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Parametric study of instantaneous heat transfer based on multidimensional model in direct-injection hydrogen-fueled engine

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ABSTRACT

This paper presents a parametric study on instantaneous heat transfer of a direct-injection hydrogen-fueled engine using a multidimensional model. A simplified single-step mechanism was considered for estimating the reaction rate of hydrogen oxidation. The modified wall-function was used for resolving the near-wall transport. An arbitrary Lagrangian–Eulerian algorithm was adopted for solving the governing equations. Experimental measurements were implemented to verify the developed model. They show that the instantaneous heat-transfer model is sufficiently accurate. The influence of engine speed, equivalence ratio, and the start of injection timing were investigated. The flow fields appeared to have greater size vectors and coarser distribution with an increase of engine speed. A heterogeneous distribution was obtained for an ultra-lean mixture condition ($\varphi \leq 0.5$), which decreased with an increase of equivalence ratio. There was no pronounced influence of the start of injection on the flow field pattern and mixture homogeneity. Thermal field analysis was used to demonstrate trends in the instantaneous heat transfer. It was observed that there was a crucial distinction between the lean and ultra-lean mixtures as well as the engine speed. Furthermore, a non-uniform behavior was found for the impact of the equivalence ratio on temperature distribution. It is clear that the developed models are powerful tools for estimating the heat transfer of the hydrogen-fueled engine. The developed predictive correlation is highly accurate in predicting the heat transfer of the hydrogen-fueled engine, focusing on the equivalence ratio as a governing variable.

1. Introduction

The growth of alternatives to the fossil-fueled internal-combustion engines (ICEs) for personal transportation offers significant prospects. They promise to reduce the dependence of the world on fossil fuels (depleted resources) and their adverse environmental effects. The challenge is to find highly efficient ways to produce, deliver, and use the energy that

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enhances the quality of life. The environment and climate are under threat. The energy carrier hydrogen is an alternative to fossil fuels which have the potential to achieve the required goals [1,2]. Development of internal combustion engines (ICEs) with hydrogen as an alternative fuel has made considerable progress [3–11]; however, many challenges still remain. Therefore, much work is under way in an attempt to overcome these hurdles [3,11–13]. An excellent technical and historical survey of the literature on H_2ICE research has been accomplished by several researchers [3,14,15]. These reviews deal with the major effects, difficulties, technical problems, efficiency improvement and economy of utilizing hydrogen as fuel for ICEs. Within this field, many studies have been presented which characterize the combustion process, overall performance and emissions of hydrogen-fueled engines [16–20]. There are few, however, which investigate heat transfer [11].

Heat transfer is one of the noteworthy issues in the study of ICEs. It has a direct effect on the main distinguishing parameters for the engine, such as in-cylinder pressure and temperature. Effort has been devoted to developing a highly efficient global heat transfer model for ICE applications [21]. An overview of the state of the art shows an abundance of correlations for estimation of heat transfer in ICEs [22]. Since 2000, the heat-transfer issue has arisen as one of the crucial features in the modeling of the hydrogen-fueled engine (H_2ICE). The importance of investigating heat transfer for H_2ICE can be ascribed to the vast differences in its properties compared with hydrocarbon fuels [23,24]. The differences relate not only to the quantity of the heat liberated from the combustion process but also the unique behavior of hydrogen combustion [25].

Several efforts have been directed towards developing realistic thermodynamic models of the engine cycle. These types of model enable a cheap and fast optimization of engine settings for operation with hydrogen fuel [26]. Several sub-models are required to solve the equations governing the conservation of energy and mass, including the combustion, turbulence, and heat transfer models. Numerous correlations in the literature have been developed to model the heat transfer in fossil fuel engines [27–29]. Existing models are based on the empirical formulation for heat transfer in hydrocarbon-fueled ICEs. However, the phenomenon of heat transfer in hydrogen and fossil-fuelled ICEs is different in the rate and behavior of heat release, as well as in the heat loss due to the different properties [25,26,30–32]. A new heat transfer model applicable to H_2ICE was proposed by Shudo and Suzuki [33] based on Woschni's model. It contains two calibration parameters that depend on the ignition timing and equivalence ratio (φ). Therefore, dependency of heat transfer correlation on the equivalence ratio is stated to be the subject of further studies [11,26,34]. It is not possible to predict accurately the trends with a variation in the equivalence ratio using a recalibration of Annand and Woschni's correlations [26]. Applicability of a quasi-dimensional heat transfer model for a hydrogen-fueled ICE (H_2ICE) was presented by Nefischer et al. [35]. This model is based on the realistic description of the characteristic velocity for the turbulent flow field proposed by Schubert et al. [36]. The predicted heat transfer was in reasonable agreement with experiments for port injection; however, the direct-injection effect was not predictable. Recent developments in the analysis of heat transfer in a H_2ICE have focused only on the instantaneous spatially averaged. This is due to the importance of the heat transfer correlation for modeling the engine cycle [26,37].

Multidimensional modeling represents the approach for modern computational fluid dynamics (CFD) codes. It provides very valuable and complete information compared with experiments of the in-cylinder flow pattern. It is difficult to simulate adequately the heat fluxes through the cylinder walls due to the unsteady and highly inhomogeneous temperature distribution of the cylinder charge, as well as the uncertainty that exists in the determination of the initial and boundary conditions of the problem [38]. CFD codes become an efficient tool for the calculation of heat transfer in ICE applications. Most current CFD codes utilize either a wall-function or a near-wall modeling approach to describe the flow conditions near the wall in the heat transfer calculations. An abundance of literature has proposed various heat transfer models, which are based on the wall-function hypothesis. The basic formula for all available models was developed by Launder and Spalding [39]. This approach is extensively considered in multidimensional simulations, because it provides a robust technique of computing the thermal boundary layer without increasing the computational nodes that are placed within this layer [40]. Of course, various formulations can be found where the number of nodes in the boundary layer is increased and there, the law-of-the-wall is applied with satisfactorily results [38]. A critical evaluation of current heat transfer models used in CFD in-cylinder engine simulations reveals that the establishment of a comprehensive wall-function formulation for estimation of the heat fluxes is included. It was assessed which wall-function formulation is more suitable for each engine type and under what operating conditions. The model of Launder and Spalding [39] revealed its weaknesses in all cases considered, as has also been demonstrated by many other researchers [40]. However, its improved version achieves the best estimation of wall heat loss [41,42]. Parametric investigations become more achievable due to the inclusion of several sub-models, which describe each phenomenon. The three dimensional compressible averaged Navier–Stoke's equations are solved on a moving mesh. Turbulent fluxes are modeled by an eddy viscosity concept using κ–ε model [43]. The present study attempts to address the influence of the equivalence ratio on multidimensional instantaneous heat transfer (IHT). IHT is devoted to weighting the influence of operating parameters on heat transfer. Therefore, the parametric study of heat transfer is essential to investigate the trends of IHT. The outcome of the present study is expected to establish a technical contribution for the automotive sectors.

2. Multidimensional engine model

A multidimensional model is used to characterize the instantaneous heat transfer for a direct-injection hydrogen-fueled internal combustion engine (DIH_2ICE). This model is based on a computational fluid dynamics approach using the finite volume technique. Fig. 1(a) shows the physical domain