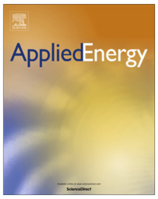
ARTICLE IN PRESS

Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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



Development of a semi-empirical convective heat transfer correlation based on thermodynamic and optical measurements in a spark ignition engine ☆

Adrian Irimescu *, Simona Silvia Merola, Cinzia Tornatore, Gerardo Valentino

Istituto Motori – CNR, Via Marconi No. 4, 80125 Napoli, Italy

HIGHLIGHTS

- A new convective heat transfer correlation was developed for spark ignition engines.
- Measurements in an experimental optical power unit were used for validation.
- Fuel effects were correctly modeled and verified with methane and hydrogen.
- Results were compared to two other widely used correlations.
- Calibration was found to be easier for the proposed model.

ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form 6 February 2015
Accepted 8 February 2015
Available online xxxx

Keywords:
Spark ignition engines
Optical measurements
Heat transfer model
Thermodynamic analysis

ABSTRACT

Internal combustion engines are still the main technology for energy conversion in automotive transport and are set to remain the main choice of propulsion solutions for some time to come. Development and design of these power units in the quest for improved efficiency and reduced environmental impact is increasingly reliant on simulations in order to reduce costs. Therefore, continuous improvement of sub-models used for numerical investigation is required so that correct and pertinent results are obtained. Convective heat transfer is receiving much attention in this respect, especially as direct injection spark ignition (DISI) engines can feature abnormal combustion phenomena such as mega-knock, mainly driven by local hot spots in the combustion chamber, that can be extremely damaging as they cannot be mitigated with existing control procedures. As a result, thermal stratification is more and more investigated through both quasi-dimensional and more complex computational fluid dynamics (CFD) codes. Alternative fuels are also extensively studied, especially as their specific properties that are different from those of gasoline can make their application challenging, thus requiring further insight in order to identify suitable injection and ignition control strategies. A new convective heat transfer correlation was developed for application in quasi-dimensional models, with a more fundamental basis combined with the application of a flow field model; results were compared to existing and extensively used empirical equations. Assessments were based on in-cylinder pressure measurements performed on a DISI engine fueled with gasoline, combined with the evaluation of flame area through optical techniques. Crank angle resolved UV–visible chemiluminescence was used for the analysis of early stage flame development and cycle resolved acquisitions were employed in order to visualize the main combustion phase. The effect of engine speed, load, spark advance and air–fuel ratio was investigated. Thermodynamic and optical data were found to be well correlated when applying the proposed model that also features simpler calibration. Further validation was performed by using heat flux measurements on another experimental power unit fueled with methane and hydrogen.

1. Introduction

The internal combustion engine has been the power unit of choice in the transport sector and is still set to be the main driver for decades to come. Therefore, intensive efforts are made in order

---

☆ This paper is included in the Special Issue of Clean Transport edited by Prof. Anthony Roskilly, Dr. Roberto Palacin and Prof. Yan.

* Corresponding author.

E-mail address: a.irimescu@im.cnr.it (A. Irimescu).

http://dx.doi.org/10.1016/j.apenergy.2015.02.050
0306-2619/© 2015 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Irimescu A et al. Development of a semi-empirical convective heat transfer correlation based on thermodynamic and optical measurements in a spark ignition engine. Appl Energy (2015), http://dx.doi.org/10.1016/j.apenergy.2015.02.050

Nomenclature

A	area (m^2)
B	cylinder bore (m)
C	coefficient (–)
h	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$) or height (m)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
N	number of samples (–)
Nu	Nusselt number (–)
p	pressure (Pa)
Pr	Prandtl number (–)
Re	Reynolds number (–)
S	speed ($m\,s^{-1}$)
t	time (s)
T	temperature (K)
U	gas or piston velocity ($m\,s^{-1}$)
V	volume (m^3)
w	characteristic velocity ($m\,s^{-1}$)

Subscripts

b	burned
c	clearance
d	displacement
f	flame
m	motored
p	piston
r	reference
u	unburned
w	wall

Abbreviations

CMOS	complementary metal oxide semiconductor
COV	coefficient of variation
DI	direct injection
EVC	exhaust valves closure
EVO	exhaust valves opening
ICCD	intensified charge coupled device
IMEP	indicated mean effective pressure
IVC	intake valves closure
IVO	intake valves opening
MFB	mass fraction burned
SI	spark ignition
SOS	start of spark
TDC	top dead center (with b- for before and a- for after)
UV	ultraviolet
VFB	volume fraction burned
WOT	wide open throttle

to continuously improve this technology and provide optimum use of classical and alternative energy sources with reduced environmental impact [1].

One of the main areas of research has become the use of alternative fuels [2]. This trend initially driven by the introduction of mandatory blending targets with biofuels, is searching to improve multi-fuel operation, given that availability will be a significant problem in the mid-term future. Alternative modes of operation such as so called ‘skip cycle’ have been proposed to improve part load efficiency of spark ignition (SI) engines [3] and exhaust heat recovery is considered for improving overall output, even if the effectiveness of such ‘bottoming cycles’ is relatively low [4,5]. The Miller cycle (traditionally employed for SI engines [6]) is also intensely studied in compression ignition power units [7] in order to provide reduced NO_x and particulate emissions.

Extensive use of simulation software for developing the next generation of engines has become an ever increasing trend for the automotive sector. In order to reduce development costs, it is routine to use simplified and less computationally demanding non- or quasi-dimensional thermodynamic models [8], as well as more complex CFD codes with comprehensive sub-models that even include crevice effects in detail [9]. Heat transfer and related phenomena represent a major part of numerical simulations and is therefore studied in the search for better understanding of normal and abnormal combustion. The importance of turbulence in heat transfer has been long recognized and several ways to account for its generation and dissipation have been investigated [10]. Specific fuel properties, such as those of hydrogen compared to conventional energy sources were also found to have a significant impact on heat losses during the engine cycle [11], and empirical equations were developed for including mixture strength in the convective correlation [12,13]. The effects of flame development were also found to be important for heat transfer, which hinders the application of simple convective models [14]. For this reason, several ways of correlating heat transfer during combustion to the mass fraction burned were sought after [15,16].

When developing heat transfer correlations, there are basically two pathways, namely taking the empirical route and that of defining the properties inside the boundary layer (e.g. by using a wall function formulation [17]). A comprehensive design of experiment identified several correlations between specific engine parameters, fluid properties as well as operational parameters, and the coefficient of convective heat transfer [18]. Therefore, it can be stated that the critical influences on heat transfer, such as characteristic length, fluid velocity and gas properties have been extensively documented via the experimental route.

Rather than taking an empirical approach, the present study looked for a more fundamental basis, where fluid motion was associated with simplified cases other than that of flow inside tubes, for which convective heat transfer correlations are available. To this end, the similarity between the motion of the largest eddies inside the combustion chamber and jets impinging on a flat plate was tested. The use of an empirically defined equation for calculating the convective heat transfer coefficient was combined with a more fundamental view of fluid velocity. The latter parameter was calculated by applying a cascade model of kinetic energy transfer, with the effect of burned gas expansion included during combustion. Combined thermodynamic and optical measurements on a SI engine featuring a transparent piston crown were used for validation, with a wide range of operating conditions with regard to engine speed, intake pressure, air–fuel ratio and spark timing. Fuel effects were evaluated based on in-cylinder pressure and heat flux measurements performed on a cooperative fuel research (CFR) engine running on methane and hydrogen. Results were also compared to values predicted by means of two widely used heat transfer correlations, namely Woschni’s [19] and that of Annand [20].

2. Materials and methods

2.1. Experimental setup and procedure

The engine used in the experimental trials features an optical access that allows combustion processes to be visualized from

Please cite this article in press as: Irimescu A et al. Development of a semi-empirical convective heat transfer correlation based on thermodynamic and optical measurements in a spark ignition engine. Appl Energy (2015), http://dx.doi.org/10.1016/j.apenergy.2015.02.050