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Semi-empirical model for the engine liquid fuel sheet formed by the oblique jet impinging onto a plate

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ABSTRACT

Operating conditions and fuel properties are important to the atomization quality, which is an inevitable problem that the liquid fuel has to face, specifically for new alternative fuels. One of the recognized atomization methods is the liquid sheet formed by the oblique fuel jet or spray impinging onto a plate in a direct injection (DI) engine. In this paper, a series of experiments that deal with the sheet, are carried out under different operating conditions. Meanwhile, a semi-empirical model fitted for new alternative fuels is established to predict the shape and the size of the sheet. The predictions of the model are in good agreement with the experimental data. Based on the experiments and predictions, the specific effect of the dynamic viscosity, the surface tension, the impingement velocity and the impingement angle on the sheet were analyzed, respectively. It is found that the sheet consists of a thin liquid layer and a thick rim which connects the outer and the inner border lines. With the decrease of the dynamic viscosity, the size of both the outer and inner border lines of the sheet will non-linearly increase. The gradient of the size of the border lines is decreased with the increase of the dynamic viscosity. With the decrease of the surface tension coefficient, the size of the border lines will gradually increase. The size of the border lines will linearly increase with the increasing impingement velocity. With the increase of the impingement angle, the border lines will gradually become circles. The semi-empirical model that is established with reasonable assumptions, can help fuel developers to assess the potential atomization quality of their new fuels.

1. Introduction

The liquid fuel sheet formed by an oblique jet impinging onto a plate is an effective way to the atomization in most kinds of engines, such as the fuel atomization in gas turbines [1], the fuel spray plate impingement in direct injection spark ignition engines [2,3], the falling film cooling in evaporators [4] and the flash boiling on the piston cavity wall in petrol engines [5]. Si [6] specially pointed out that the sheet caused by the piston cavity wall impingement in direct injection diesel engine has a very strong influence on the spray development, mixture formation and the combustion. Based on the energy conversion, the atomization is the process to tear the fuel apart with the help of external kinetic energy, and the fuel sheet is right a key part of the process. Recently, the development of the new fuel has brought many kinds of biodiesel as the alternative fuel, for instance, the di-n-butyl ether blending with the soybean-biodiesel [7] and the diesel/methanol dual fuel [8]. On the one hand, researchers gradually noticed that regardless of the fuel itself, the fuel properties are the essential problem that bears the brunt. For example, Wang [9] found that the fuel properties are the main factors affecting the spray and the subsequent atomization by using the naphtha and surrogate fuels. A full distillation fuel was developed by Wang [10], who tried his best to make sure that the new fuel viscosity is the same as that of the diesel for the reason that the properties of the alternative fuel will change the atomization quality obviously [11]. The impact of the properties of the new fuels on the atomization are also involved in the model of Zhan [12]. On the other hand, researchers also noticed that the influence of the fuel property appears in almost any engines. Taghavifar [13] addressed the plate heat flux modeling of n-heptane fueled direct injection diesel engine, and found that the mass flow, the pressure and the evaporation rate are playing important roles during the whole process. Li [14] indirectly proved that changing the injector geometry, jet velocity and other factors is an effective way to deal with changes in the fuel properties. Therefore, the atomization depends on the accurate shape and size of the fuel sheet which totally calls for the operating parameters and the fuel properties [6,15].

In order to make all the new fuels in engines be applied easily, Roy [16] mentioned a gene expression programming that is to control the

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Nomenclature

Notation

A	the area of the contact surface (m^2)
A_0	the cross-sectional area of the jet (m^2)
f_k	the loss of the velocity in x direction caused by the impingement
f_τ	the proportionality function of the shear stress
f_σ	the proportionality function that indicates the effect of the surface tension
h	the thickness of the sheet (m)
h_0	the initial thickness of the sheet (m)
$\overline{h_f}$	the average thickness of the flow tube (m)
$\overline{h_\phi}$	the average thickness of the flow tube (m)
k_1	the constant parameter
L_t	the circumference of the contact surface (m)
l_x	the length of the streamline (m)
l_{max}	the maximum length of the streamline (m)
l'_{max}	the maximum Length of streamline of the thin-layer zone (m)
$\dot{M}$	the mass flow of the jet (kg/s)
$\dot{M}_z$	the mass flow of the jet in z direction (kg/s)
$\dot{M}_{zi}$	the mass flow of the streamline in z direction (kg/s)
$\dot{q}_S$	the dissipation energy (J/s)
R	the radius of jet (m)
r	the length of streamline in contact surface (m)
t	the time scale of the impingement (s)
u_r	the radial velocity (m/s)
u_z	the velocity in z direction (m/s)
V_0	the jet impingement velocity (m/s)
V_{0r}	the radial velocity of the jet that V_{0z} transforms into (m/s)
V_{0ri}	the radial velocity of the streamline that V_{0z} transforms into (m/s)
$V_{0rx,y}$	the velocity of V_{0r} in x and y direction (m/s)
V_{1l}	the initial radial velocity (m/s)
V_{2l}	the radial velocity on the inner border line (m/s)
$V_{0x,z}$,	the jet impingement velocity in x, z direction (m/s)
$V_{1x,y}$,	the velocity of V_{1l} in x and y direction (m/s)
V_l	the radial velocity of the sheet (m/s)
V_{lmax}	the maximum radial velocity of the sheet (m/s)
V_n	the velocity in the raised zone (m/s)
θ	the jet impingement angle (°)
μ	the viscosity coefficient (pa·s)
τ	the viscous shear stress (N/m^2)
ρ_l	the liquid density (kg/m^3)
σ_l	the surface tension coefficient (N/m)
ϕ	the azimuthal angle of sheet (°)
φ	the azimuthal angle of contact surface (°)
ψ	the energy dissipation rate per time and volume unit, (J/($s{\cdot}m^3$))
$\varnothing_0$	the angle between the streamline and the tangent line of the contact surface (°)
$\varnothing_1$	the angle between radial velocity and tangent line of the outer border line (°)

Subscripts

l	Liquid
r	Radial
x, y, z	In x, y, z direction

engine. The gene expression programming is intended to fit the engine in variable operating conditions and fuel properties. This paper aims to provide a simple semi-empirical equation by a complex fluid dynamics derivation process for fuel developers, such as Roy [16]. Therefore, it is important to predict the shape, the size and the thickness of the liquid fuel sheet in a variety of conditions.

Dombrowski [17] listed almost all the methods to form a liquid sheet. At present, there are two methods to form a liquid sheet, the oblique jet impinging onto a plate (the plate impingement jet) and the impinging-jets. The impinging-jets is two symmetrical jets impinging, a flat liquid sheet is produced in a plane perpendicular to that containing them [18]. The plate impingement jet can be seen as the splash plate nozzle with an infinity plate and the liquid will be attached the plate rather than splashing [19]. The splash plate nozzle typically consists of an oval shaped flat plate attached at an angle to the end of a pipe [20]. The splash plate nozzle is also used for the atomization and has been analyzed by the theory of Inamura [21] and the numerical simulation of Sarchami [22].

In the previous studies on impinging-jets, Huang [23] found that there are three break-up regimes in the Weber number range from 100 to 30000. Chubb [24] found that the rim of the sheet is existing, the shape of the rim is an ellipse. Bremond [25] deduced the specific parameters of the rim. Ahmed [20] found that the break-up occurs on the rim. To study the sheet, Taylor [26] proposed three key parameters that includes the thickness, the break-up length and the velocity by a lot of experiments and theoretical analysis. Based on the model of Taylor [26], Hasson [27] improved the thickness model by analyzing the streamlines in the sheet. Shen [28] carried out experiments to verify the thickness model of Hasson [27]. Choo [29] started from the jet impingement velocity based on the model of Taylor [26], he found that the direction of the velocity in the sheet is radial and the velocity changes with different azimuthal angles. Li [30] further proposed that the velocity in the sheet is the non-uniform distribution. In order to control the velocity in the sheet, the easiest way is to control the jet impingement velocity. Therefore, Inoue [31] found that the non-uniform jet impingement velocity profile results in a velocity in the sheet. The last key parameter is the break-up length that is the length of the sheet, for the sheet is destined to the break-up. To get the break-up length, it is necessary to get to know the break-up mechanism. Ibrahim [32] found that the break-up is due to the Taylor-Plateau wave when the Weber number is lower then 500, the break-up is due to the Kelvin-Helmholtz wave when the Weber number is higher then 2000. Dombrowski [18] and Jung [33] conducted turbulence and laminar experiments to verify the theory proposed by Ibrahim [32], respectively. Based on the break-up mechanism, Anderson [34] established the linear stability theory to describe the break-up of the sheet. Chojnacki [35] proved that the theory of Anderson [34] applies to non-Newtonian liquids as well. In summary, the three key parameters, which are affected by operating conditions, are very important for the sheet properties. Therefore, researchers studied the effect of the different operating conditions. For example, Lai [36] analyzed the effect of the surface tension on the sheet, Heislbetz [37] analyzed the effect of the dynamic viscosity of Newtonian liquids on the sheet, Yang [38] established a mature model to analyze the effect of the Weber number and the Reynolds number on the sheet, etc. Based on these mature models, some new impinging-jets models have emerged, such as the unlike impinging-jets [39] and the power-law impinging-jets [40]. The sheet formed by the impinging-jets is for the atomization, the characteristic of the atomization is totally depend on the shape of the sheet [15]. Inoue [41] also proved that the velocity in the sheet directly affected the atomization. Based on previous studies, Inoue [42,43] established the model to predict the Sauer mean diameter and the droplet distribution of the atomization, respectively. The plate impingement jet is similar to the impinging-jets, thus the analysis and derivation methods of the