Fuel xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fuel

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

A novel theoretical approach to the temperature–viscosity relation for fluidic fuels

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HIGHLIGHTS

- Novel theoretical approach to the viscosity of fluidic fuel was constructed.
- Equation for viscosity over temperature was derived.
- Viscosity decreased with temperature, but increased in high temperature region.
- Good agreements with the reported data from references were found.

ARTICLE INFO

Article history:
Received 23 May 2014
Received in revised form 25 February 2015
Accepted 26 February 2015
Available online xxxx

Keywords:
Fluidic fuel
Viscosity
Temperature
Interaction potential
Momentum transfer

ABSTRACT

Viscosity is a first and foremost function both for theory and application. By approximating the interaction potential of molecule in fluidic fuel as constant and proposing a new method to calculate the momentum transfer by means of the radius of averaged volume per molecule, an equation of viscosity versus temperature was derived, which were found in good agreement with a lot of data from gaseous to liquid fuels by the curve fit. The equation also predicted that the viscosity initially decreased with temperature and then slowly increased in the high temperature region. When using it as correlation equation for the dependence of viscosity on temperature, it was able to cover more fluids from gaseous to liquid fuels.

1. Introduction

Fluidic fuel includes liquid and gaseous fuels. They are the major types of chemical fuels that cannot be replaced in industrial and daily life up to now. Knowledge of the viscosity of fluidic fuel is important since it determines the temperature for handling, the size of the centrifuges and the temperature at which the fuel is injected into the engine. In these process, the relation between viscosity and temperature plays a crucial role.

Because of the importance in theory and practice, there has long been an effort to find the equation that can be applied for more fluids in wider temperature and viscosity ranges. Since Reynolds presented the first equation correlating the viscosity and temperature [1], a lot of equations were reported subsequently, which can be classified into three forms: the early form, the Arrhenius and the log–log forms. The early formula such as Reynolds' [1] and Vogel's [2] could only cover narrow temperature and viscosity range. The Arrhenius form included the Arrhenius equation, Williams–Landel–Ferry equation, Fulcher's [3], and improved Vogel equation. The more complicated log–log form was also used in the attempt to cover wider temperature and viscosity ranges [4,5]. Because of the importance in fuel production, transportation, storage and application, attentions have been especially paid to the temperature dependent viscosity models or correlations for fluidic fuels, such as for crude oils [6,7], for predicting natural gas viscosity [8], for biodiesel [9–16], for mixed oil [17] and waxy oils [18], for petroleum reservoir fluids [19], for lubricants [20], for hydrocarbon Fractions [21] and light hydrocarbon solvents [22]. Most equations from the mentioned references were constructed on pure experience of single or a type of fuel/crude fuel to fit the experimental data in various ranges of temperature and viscosity. As a result, they can hardly be applied to the whole fluidic fuels of both gas and liquid. It is always desired to construct an ideal equation that has theoretical background and is able to cover both liquid and gaseous fuels in wider temperature and viscosity ranges.

In present paper, the author approximated the molecular interaction in the fluidic fuel as constant potential, and derived novel

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http://dx.doi.org/10.1016/j.fuel.2015.02.115
0016-2361/© 2015 Published by Elsevier Ltd.

Please cite this article in press as: Yang X, Li W. A novel theoretical approach to the temperature–viscosity relation for fluidic fuels. Fuel (2015), http://dx.doi.org/10.1016/j.fuel.2015.02.115

Nomenclature and symbols

A	constant
b	thickness of the layer
C	Sutherland's constant
E_i	averaged intermolecular interaction potential in J mol^{-1}
F	averaged force vector
k	Boltzmann's constant
m	mass of molecule
n	molecule density or number of data points
N	total number of molecules
N_A	Avogadro constant
r	radius of molecular space
R	universal gas constant
T	absolute temperature
T_i	interaction temperature in kelvins
T_0	reference temperature in kelvins
u	potential field
U	shear velocity
V	volume
v_x	x components of molecular velocity
v_y	y components of molecular velocity
v_z	z components of molecular velocity
Greek letters	
$\dot{\gamma}$	shear rate
ε	averaged intermolecular interaction potential
η	viscosity
η_0	viscosity constant
τ	shear force
σ	collision cross-section of molecule
Subscripts	
cal	calculated value
i	interaction
x	x-coordinate
y	y-coordinate
z	z-coordinate
0	constant

formula of viscosity versus temperature for the fluidic fuel based on statistical mechanics. Finally, comparison between the theoretical data and the experimental data gathered by author was given.

2. Theoretical

2.1. Approximation to interaction potential inside fluidic fuel

Because of the huge number of molecules, it is usually too complex to accurately calculate the intermolecular interaction inside the fluidic fuel. However, approximations of various degree of accuracy can be made while expressing the intermolecular interaction by potential function.

Inside a liquid fuel, and away from the boundary, molecules are surrounded by other molecules of the same type and are thus attracted in all directions equally. This is saying that there is no net force on molecules inside the liquid fuel. This feature is mathematically expressed as $\boldsymbol{F} = -\nabla u \approx 0$, here u denotes the potential a molecule feels. The solution of this equation is u = constant, which presents a constant potential inside the liquid fuel.

Since the gaseous fuel molecule almost moves freely, its amount of potential can be considered as a constant that approximately equal to zero ($u \approx 0$). Mathematically, the constant potential inside fluidic fuel can be simply derived by taking the zeroth-order approximation in the Taylor expansion of the potential function.

2.2. A distribution function for fluidic fuel

According to statistical mechanics, the distribution function is applicable to describe the molecules inside fluidic fuel. Upon the above approximation and presenting the constant potential of interaction as ε, the following formula of distribution function for the molecule in fluidic fuel in thermal equilibrium was proposed,

$$f = n \exp\left(\frac{\varepsilon}{kT}\right)\left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}} \exp\left[-\frac{m\left(v_x^2 + v_y^2 + v_z^2\right)}{2kT}\right] \tag{1}$$

where $n = N/V$ denotes the molecule density of the fluid, N is the total number of molecules restricted in volume V. k is Boltzmann's constant, T is absolute temperature. m is the mass of molecule, v_x, v_y, v_z are the x, y, z components of molecular velocity.

2.3. The temperature dependence of viscosity for fluidic fuel

In order to calculate the viscosity of fluidic fuel, formula for the shear stress should be obtained first. As an approximation, the shear stress in a fluid is calculated by the momentum transfer across shear surface. In liquid, the steric resistance forbids most molecules to get across the shear surface through Brownian random motion except the ones nearby the shear surface. In gas, the collision changes the direction of most molecules moving toward the shear surface before it gets across the shear surface, except the ones nearby the shear surface in the range of mean free path. Therefore, only the part of molecules in fluidic fuel nearest the shear surface interchanges molecular momentum through random motion in the y-direction (Fig. 1). Upon this consideration, the net shear stress from the momentum transfer is expressed as

$$\tau \approx \frac{2r}{b}\int_0^{\infty} mU v_y f \, dv_x dv_y dv_z = n \exp\left(\frac{\varepsilon}{kT}\right)\sqrt{\frac{mkT}{2\pi}}\frac{Ur}{b} \tag{2}$$

Here, U denotes the shear velocity to the fluid layer considered, b the thickness of the layer, r the radius of the averaged volume per molecule, which presents the linear dimension of the effective space occupied by a molecule in the fluidic fuel. In liquid r approaches the radius of a real molecule. In gas $2r$ denotes the mean free path. If a gaseous fuel were sufficiently compressed, r should reduce to the real radius of the gas molecule.

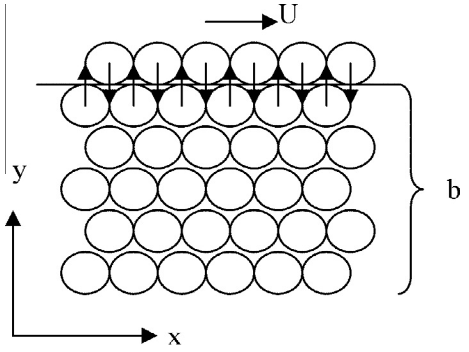

Fig. 1. The momentum transfer from the molecular exchange between nearby molecules in a fluid. b = thickness of a layer, U = the shear velocity to the fluid layer at shear surface. Sphere notes a model of the averaged volume occupied by a molecule.

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