

Paper

Kinematic Viscosity of Mechanically Emulsified Gas Oil

Hiroki ISHIDA

Department of Electronic Control Engineering, Nagaoka National College of Technology

Kinematic viscosity of the emulsified Gas oil, produced mechanically by a gear pump type mechanical emulsifier, was examined. The effects of some conditions for emulsification; the temperature, the content of water and the revolution of driving gear of the emulsifier, on the kinematic viscosity were studied experimentally. The present study revealed some important dependence of the kinematic viscosity on the running conditions of the gear pump type mechanical emulsifier. The kinematic viscosity increases with increases in the water content and in the gear revolution, but decreases with increase in the temperature of emulsion.

Key Words: *W/O type emulsion, gear pump mechanism, kinematic viscosity, Gas oil*

1. Introduction

In the recent several years, as same as in over about thirty years ago, the technology of application of emulsion fuels to many boilers, furnaces and diesel engines has attracted much attention from the point of view of the energy saving and of the prevention of atmospheric pollution caused by the exhaust from many combustion facilities. It is, mainly, due to the recent high cost of crude oil and to the prevalence of the national consensus of the protection of environment.

The kind of emulsion fuels, consisting of usual petroleum fuels and water, is divided into two types; W/O and O/W emulsions. W/O type emulsion fuel has dispersed many fine water particles in the base petroleum fuel. On the other hand, O/W type emulsion fuel has, inversely, dispersed many fine petroleum fuel particles in the water phase.

Many excellent studies on the combustion of emulsified petroleum fuels in furnaces have been reported experimentally^{1-4,8-17,21-23,25-32,34,37,38,41)} and theoretically^{5-7,11,35)}. From the point of view of fire hazard prevention also, some studies have reported the pool burning characteristics of emulsified

petroleum fuels^{10,15, 18-20, 24, 36)}. An excellent review by Kadota and Yamasaki has reported the recent advances of the study on the emulsion combustion⁴⁰⁾. In the recent decade, some studies have reported the new technology for the emulsification of miscellaneous fuels^{33,39,41,42)}.

Since over twenty years ago, Nakayama has devised and improved successfully an excellent mechanical emulsification device using a gear pumping mechanism consisting of some specified gears, which is described in his patent⁴³⁾. This mechanical emulsification device gives a strong shear stress to the mixture of water and petroleum fuel in the squish among the rotating gears and in the clearance between the gears and surrounding housing wall. Water particles are thereby strongly ground and mixed with base petroleum fuel, and some of them become extremely fine (less than about 10 μ m in diameter), which cannot be attained by the usual mechanical methods of mixing, atomizing or both. This mechanical emulsification device has enabled also the new recycling fuel technology for some waste oils (from machine and food) in boilers and many combustion furnaces.

Our previous paper has reported some important

performance of the gear pump type emulsification device including the stability of emulsions of Gas oil and A-heavy oil^{44,45}. Now the kinematic viscosity of emulsified fuel also is an important property for the characteristics of sprayed fuel jet into many combustion furnaces. In general, the decrease in the kinematic viscosity of fuel leads to the wide-angle spray area and the short length of fuel jet from the exit of nozzle. On the other hand, the increase in the kinematic viscosity of fuel leads to the long length of fuel jet from the exit of nozzle although the spray area angle will decrease. The present study reports the kinematic viscosity of the emulsified Gas oil, produced by the gear pump type mechanical emulsifier^{44,45}.

2. Gear Pump Type Emulsifier

The concept and the outline of the three gears pump type mechanical emulsifier used in this study are described in our previous paper⁴⁴. **Figures 1** and **2** show the top and the side views of the present gear pump type emulsifier, where the first gear is driven directly by a motor at 300~1300 rpm. This emulsifier has a series of 3 gears: the diameters of gear tip circle and pitch circle; 27.5~22.5 mm and 25~20 mm respectively, the numbers of teeth; 20~16, the modules of gears; 1.25~1.23, the teeth length in the axis direction of gears; 40 mm. The clearance between the gear tip and the housing wall; 0.05 mm for the first gear, 0.5 mm at one side of the second gear, about 0.15 mm at one side of the third gear and about 0.4 mm at the opposed side of the third gear. Owing to the very strong shear stress in the wider clearances around the second and the third gears, the fuel and water are mixed and emulsified.

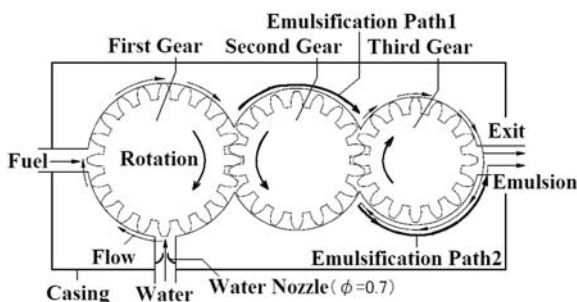


Fig.1 The scheme of top view of mechanical emulsifier (3 Gears type) used in this study.

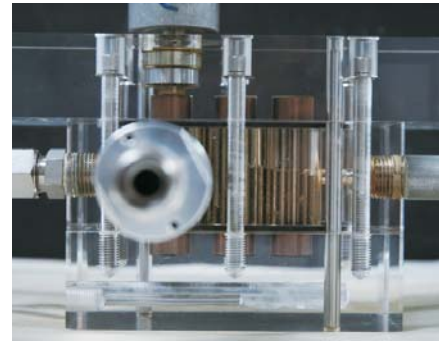


Fig.2 The side view of mechanical emulsifier (3 Gears type) used in this study.

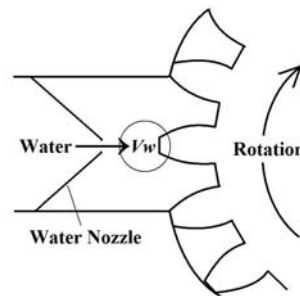


Fig.3 Scheme of the water injection (Velocity: V_w) from the fine exit of nozzle to the first gear for the emulsification.

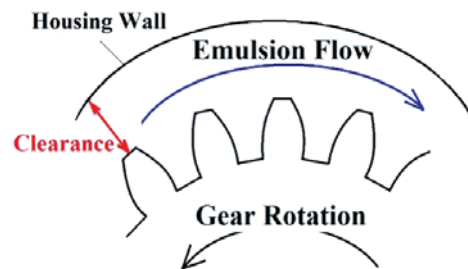


Fig.4 Schematic model of the emulsification region in the clearance between the gear teeth and the housing wall.

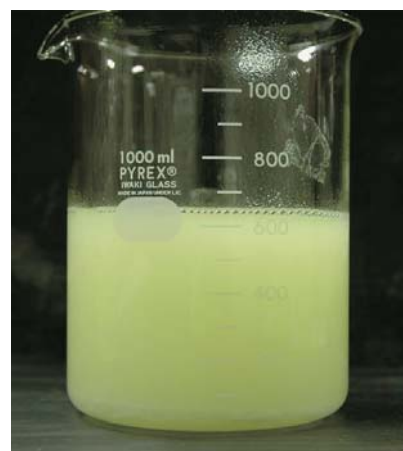


Fig.5 Representative photograph of emulsified Gas oil (Water: 9 vol.% for Fuel, 800 rpm).

In the present mechanical emulsifier, water is transported by water pump and injected at high speed (9~13 m/s) from the fine exit hole (0.7 mm in dia.) nozzle toward the first gear aiming to enhance the emulsification effect, as shown in **Fig.3**.

Figure 4 shows the schematic model of emulsification region in the wider clearance (Emulsification Path shown in **Fig.1**) between the gear tip and the housing wall. In this wider clearance the mixture of fuel and water is transferred (by the pressure due to the revolution of the first gear) in the opposite direction to the revolution of the second gear.

Although the theoretical explanation of this emulsification mechanism is not easy and cannot be given in the present stage, it should be noted that there is no other region for the emulsification except this wider clearance, where the very strong shear stress exists. We can expect thereby that the increase in the revolution of gear will enhance the stability of emulsion.

A typical W/O emulsified Gas oil is shown in **Fig.5**, where the water content is about 9 vol.% for Gas oil. As shown in this photograph, the color of W/O type emulsified Gas oil become whitish compared with that of the original Gas oil.

3. Kinematic Viscosity

The kinematic viscosity of the W/O type emulsified Gas oil in this study was measured by usual Cannon-Fenske Viscometer shown in **Fig.6**.

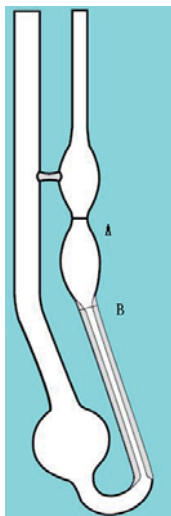


Fig.6 Cannon-Fenske Viscometer.

By the elapsed time of flow down of emulsion (T), from A to B shown in **Fig.6**, and the characteristic viscometer constant (C), the kinematic viscosity (ν) of emulsified Gas oil can be estimated as follows;

$$\nu = \mu / \rho_m = CT \quad (1)$$

where μ is the viscosity of emulsion, and ρ_m is the density of emulsion.

Figures 7, 8 and 9 show the effects of the temperature, the water content and the revolution of the first gear on the kinematic viscosity of the W/O type emulsified Gas oil respectively.

The density of emulsion (ρ_m) may be expressed as follows, using the ratio of water in emulsion (W);

$$\rho_m = \rho_A(1-W) + \rho_w W \quad (2)$$

where ρ_A is the density of Gas oil (0.82 g/cm³), and ρ_w is the density of water (1.0 g/cm³). At the standard state; 20°C, the kinematic viscosities (ν) of water and Gas oil are about 1.0 (mm²/s) and 2.7 (mm²/s) respectively.

From the result shown in **Fig.7**, we can see an interesting and important fact that the kinematic viscosity of W/O type emulsified Gas oil is slightly higher than those of original Gas oil and of the estimation by volume fractions of Gas oil and water. This may be attributable to the existence and the motion of many fine water particles. In addition, the kinematic viscosity decreases only slightly with increase in the near room temperature.

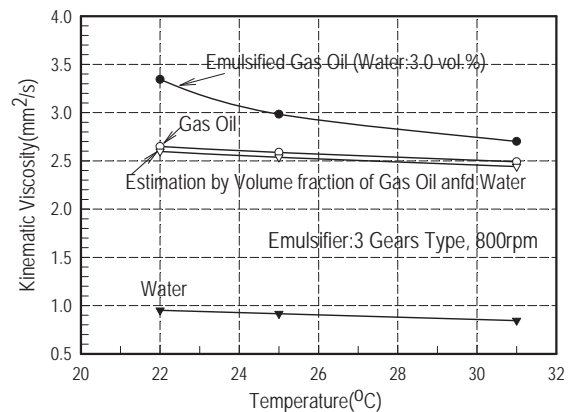


Fig.7 Effect of temperature on the kinematic viscosity.

From the **Eq. (1)**, we can assume that the change of kinematic viscosity of emulsion due to the water content is small because the viscosity of emulsion can be assumed to increase with increase in the density. From the results shown in **Figs.8** and **9**, however, we can see obviously that the increase both in the water content and in the gear revolution increases the kinematic viscosity of emulsion.

The increase in the water content will mean the increase in the number of fine water particles in emulsion, shown in **Fig.10**. The increase in the gear revolution will lead to the strong smash of water particles in the emulsification path (shown in **Fig.1**) and to the extremely finer water particles in the emulsion. Thus, the increase both in the water content and in the gear revolution will increase the contact surface area between the water and the hydrocarbon fuel.

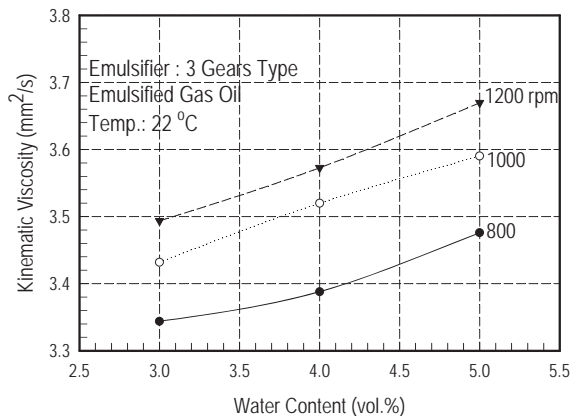


Fig.8 Effect of water content on the kinematic viscosity.

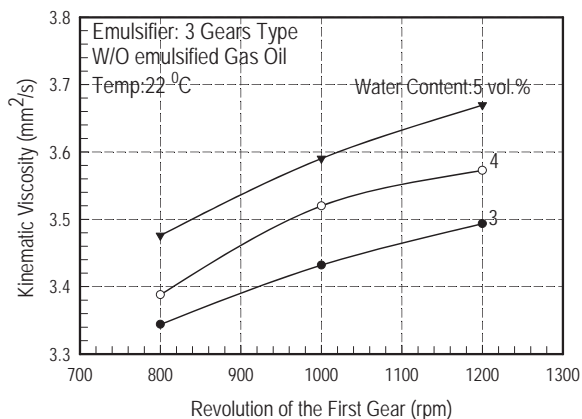


Fig.9 Effect of revolution on the kinematic viscosity.

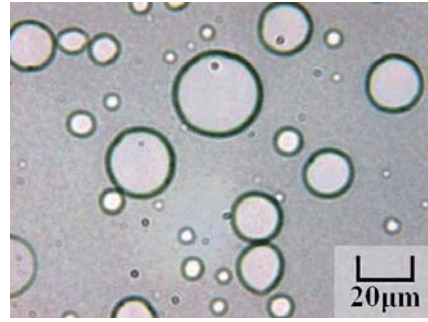


Fig. 10 Microscopic Photograph of Water Particles in the Emulsified Gas Oil (Water: 9 vol.%, 800 rpm).

The increase in the contact surface area will increase the kinematic viscosity of emulsion. We can find many reports through the Internet, referring the increase in the kinetic viscosity of emulsion due to the increase in the water content and to the decrease in the size of water particles.

4. Concluding Remarks

For the kinematic viscosity of the W/O type emulsions of Gas oil, produced by the gear pump type mechanical emulsifier without surface-active agent, the present study revealed some interesting and important characteristics as follows;

(1) The kinematic viscosity of W/O type emulsified Gas oil is higher than that of original Gas oil, which may be due to the existence of many fine water particles.

(2) Both the increase in the water content and the increase in the gear revolution increase the kinematic viscosity of W/O type emulsified Gas oil.

(3) The increase in the kinematic viscosity of W/O type emulsion may be attributable to the increase in the contact surface area between the water and the original hydrocarbon fuel.

Acknowledgments: The author would like to express his sincere thanks to Mr. T. Nakayama, N-Techno Co., Ltd. for his great help in constructing the experimental setup and providing the gear pump type mechanical emulsifier. Messrs. S. Tai and Y. Kosuge are appreciated for their great help in the experiment. The author is indebted for the financial support by Sasaki Environment Technology Foundation through this study.

References

- 1) Dryer, F.L.: *Water Addition to Practical Combustion Systems-Concepts and Applications*. Proc. Combust. Inst., Vol.16, pp. 279-295, 1976.
- 2) Sjorgen, A.: *Burning of Water-in-Oil Emulsions*, Proc. Combust. Inst., Vol.16, pp. 297-305, 1976.
- 3) Jacques, M.T. et al.: *The Combustion of Water-in-Oil Emulsions and The Influence of Asphaltene Content*, Proc. Combust. Inst., Vol.16, pp. 307-319, 1976.
- 4) Hall, R.E.: *The Effect of Water/Residual Oil Emulsions on Air Pollutant Emissions and Efficiency of Commercial Boilers*, Journal of Engineering for Power, Transactions of ASME October, pp. 425-433, 1976.
- 5) Jacques, M.T.: *Transient Heating of a Emulsified Water-in-Oil Droplet*, Combustion and Flame, Vol.29, pp. 77-85, 1977.
- 6) Birchley, J.C. and Riley, N.: *Transient Evaporation and Combustion of a Composite Water-Oil Droplet*, Combustion and Flame, Vol. 29, pp. 145-165, 1977.
- 7) Law, C.K.: *A Model for the Combustion of Oil/Water Emulsion Droplets*, Comb. Sci. and Tech., Vol. 17, pp. 29-38, 1977.
- 8) Cook, D.H. and Law, C.K.: *A Preliminary Study on the Utilization of Water-in-Oil Emulsions in Diesel Engines*, Comb. Sci. and Tech., Vol. 18, pp. 217-221, 1978.
- 9) Lasheras, J.C., et al.: *Initial Observations on the Free Droplet Combustion Characteristics of Water-in-Fuel Emulsions*, Comb. Sci. and Tech., Vol. 21, pp. 1-14, 1979.
- 10) Weatherford Jr., W.D., et al.: *Army Fire-Resistant Diesel Fuel*, SAE Technical Paper Series, No. 790926, 1979.
- 11) Law, C.K., et al.: *Combustion Characteristics of Water-in-Oil Emulsion Droplets*, Combustion and Flame, Vol. 37, pp. 125-143, 1980.
- 12) Jahani, H. and Gollahalli, S.R.: *Characteristics of Burning Jet A Fuel and Jet A Fuel-Water Emulsion Sprays*, Combustion and Flame, Vol. 37, pp. 145-154, 1980.
- 13) Lasheras, J.C., et al.: *On the Disruptive Burning of Free Droplets of Alcohol/n-Paraffin Solutions and Emulsions*, Proc. Combust. Inst., Vol. 18, pp. 293-305, 1981.
- 14) Gollahalli, S.R., et al.: *Combustion of Drops and Sprays of No.2 Diesel Oil and Its Emulsions with Water*, Proc. Combust. Inst., Vol. 18, pp. 349-360, 1981.
- 15) Law, C.K.: *On the Fire Resistant Nature of Oil/Water Emulsions*, Fuel, Vol. 60, pp. 998-999, 1981.
- 16) Marrone, N.J., et al.: *Internal Phase Size Effect on Combustion of Emulsions*, Comb. Sci. and Tech., Vol.33, pp. 299-307, 1983.
- 17) Yap, L.T., et al.: *Disruptive and Micro-Explosive Combustion of Free Droplets in Highly Convective Environments*, Comb. Sci. and Tech., Vol. 41, pp. 291-313, 1984.
- 18) Ishida, H. and Iwama, A.: *Ignition Characteristics of Gelled (O/W Emulsified) Hydrocarbon Fuel Pool*, Comb. Sci. and Tech., Vol. 36, pp. 51-64, 1984.
- 19) Ishida, H. and Iwama, A.: *Flame Spreading along the Surface of Gelled (O/W Emulsified) Hydrocarbon Fuel pool*, Comb. Sci. and Tech., Vol. 36, pp. 65-82, 1984.
- 20) Ishida, H. and Iwama, A.: *Flame Spread along Gelled (O/W Emulsified) Pool of High-Volatile Hydrocarbon Fuel*, Comb. Sci. and Tech., Vol. 37, pp. 79-92, 1984.
- 21) Wang, C.H. and Law, C.K.: *Microexplosion of Fuel Droplets under High Pressure*, Combustion and Flame, Vol. 59, pp. 53-62, 1985.
- 22) Kimura, M., et al.: *Combustion behaviors of Emulsified Petroleum and JP-4/N₂H₄ Droplets at Weightless and Free falling Conditions*, Comb. Sci. and Tech., Vol. 44, pp. 289-306, 1986.
- 23) Randolph, A.L. and Law, C.K.: *Time-Resolved gasification and Sooting Characteristics of Droplets of Alcohol/Oil Blends and Water/Oil Emulsions*, Proc. Combust. Inst., Vol. 21, pp. 1125-1131, 1986.
- 24) Ishida, H. and Watanabe, H.: *Flame Suppression over Liquid Pool by W/O Emulsification*, Comb. Sci. and Tech., Vol.71, pp. 145-154, 1990.
- 25) Adiga, K.C. and Shah, D.O.: *On the Vaporization Behavior of Water-in-Oil Microemulsions*, Combustion and Flame, Vol. 80, pp. 412-414, 1990.
- 26) Chung, S.H. and Kim, J.S.: *An Experiment on Vaporization and Microexplosion of Emulsion Fuel Droplets on a Hot Surface*, Proc. Combust. Inst., Vol. 23, pp. 1431-1435, 1990.
- 27) Yamasaki, H. and Tsue, M.: *Evaporation and Combustion of Emulsified Fuel*, JSME Int'l J. (B), Vol. 36, pp. 677-681, 1993.
- 28) Ballester, J.M., et al.: *Detailed Measurements in Heavy Oil and Oil/Water Emulsion Flames*, Comb. Sci. and Tech., Vol. 106, pp. 383-391, 1995.
- 29) Tsue, M., et al.: *Observation of Sooting Behavior in Emulsion Droplet Flame by Planar Laser Light Scattering in Microgravity*, Proc. Combust. Inst., Vol. 26, pp. 1251-1258, 1996.
- 30) Tsue, M., et al.: *Statistical Analysis on Onset of Microexplosion for an Emulsion Droplet*, Proc. Combust. Inst., Vol. 26, pp. 1629-1635, 1996.
- 31) Yamasaki, H., et al.: *Time Histories of Water Contents in a Burning Emulsion Droplet*, Proc. The First Asia-Pacific Conf. on Combustion, pp. 603-606, 1997.
- 32) Tsue, M., et al.: *Effect of Gravity on Onset of Microexplosion for an Oil-Water Emulsion Droplet*, Proc. Combust. Inst., Vol. 27, pp. 2583-2593, 1998.
- 33) Kufferath, A., et al.: *Continuous Generation and Air-Assisted Atomization of Fuel Oil-Water-Emulsions*, Comb. Sci. and Tech., Vol. 148, pp. 17-26, 1999.
- 34) Nachmoni, G. and Natan, B.: *Combustion Characteristics of Gel Fuels*, Comb. Sci. and Tech., Vol. 156, pp. 139-157, 2000.
- 35) Leite, L.F.T. and Lage, P.L.C.: *Modeling of Emulsion Droplet Vaporization and Combustion Including Microexplosion Analysis*, Comb. Sci. and Tech., Vol. 157,

- pp. 213-242, 2000.
- 36) Walavalkar, A.Y. and Kulkarni, A.K.: *Combustion of Water-in-Oil Emulsion Layers Supported on Water*, Combustion and Flame, Vol. 125, pp. 1001-1011, 2001.
 - 37) O-Barrera, R. and Vilasenor, R.: *An Experimental study of the Effect of Water Content on Combustion of Heavy Fuel Oil/Water Emulsion Droplets*, Combustion and Flame, Vol. 126, pp. 1845-1855, 2001.
 - 38) Gong, J-S. and Fu, W-B.: *A Study on the Effect of More Volatile Fuel on Evaporation and Ignition for Emulsified Oil*, Fuel, Vol. 80, pp. 437-445, 2001.
 - 39) Dantas, T.NdeC., et al.: *New Microemulsion System using Diesel and Vegetable Oils*, Fuel, Vol. 80, pp. 75-81, 2001.
 - 40) Kadota, T. and Yamasaki, H.: *Recent Advances in the Combustion of Water Fuel Emulsion*, Progress in Energy and Comb. Sci., Vol. 28, pp. 385-404, 2002.
 - 41) Hernandez, J.F. and Morla, J.C.: *Fuel Emulsions Using Biomass Pyrolysis products as an Emulsifier Agent*, Energy & Fuels, Vol. 17, pp. 302-307, 2003.
 - 42) Wang, C.H. et al.: *Combustion and Micro-explosion of Collision-merged Methanol/Alkane Droplets*, Proc. Combust. Inst., Vol. 30, pp. 1965-1972, 2005.
 - 43) Nakayama, T.: International Patent Application, B01F 3/08 (2006.01), No. PCT/JP2005/022850 (WO 2007/069298 A1).
 - 44) Ishida, H. and Tachibana, K.: *A mechanical Emulsification Technology of Petroleum fuels without Surface Active Agent*, Research Rep. of Nagaoka National College of Technology, Vol. 45, No.2, pp. 47-54, 2009.
 - 45) Ishida, H.: *Kinematic Viscosity of Mechanically Emulsified A-Heavy oil*, Research Rep. of Nagaoka National College of Technology, Vol. 46, pp. 25-29, 2010.

(Received August 2, 2012)