A Mechanical Emulsification Technology of Petroleum Fuels Without Surface Active Agent

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Abstract

A mechanical emulsification device using a gear pumping mechanism consisting of some specified gears has been studied and developed to improve emulsification performance of petroleum fuel oils. By using the gear pump type emulsifier; stable W/O type emulsions of gas oil and of A-heavy oil can be produced successfully without surface-active agent. The study revealed some interesting and important characteristics of the mechanical emulsification process; the limiting content of water, the limiting revolution of the driving gear, the stability of emulsion, and the emulsification performance and discharge rate of the emulsifier.

Key words: *W/O type emulsion, Gear pump mechanism, Micro-explosion, Gas oil, A-Heavy oil*

1. INTRODUCTION AND BACKGROUND

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.

The ideas of combustion of emulsified petroleum fuels by mixing with water in many commercial furnaces have been reported since many years ago. Many excellent studies have reported them 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 combustion[40)]. In the recent decade, some studies have reported the new technology for the emulsification [33,39,41,42)].

2. EMULSION FUEL COMBUSTION

The main advantage of emulsion combustion is due to the characteristic combustion behaviors of the sprayed emulsified fuel droplets, caused by the included many fine water particles in each droplet. The diameters of the liquid fuel droplets sprayed into the combustors are, usually, in the range of 30~130 μm. Under the usual standard atmospheric pressure, the volume of one water droplet is expanded about 1700 times larger than the original droplet volume due to the vaporization.

Namely, in the high temperature atmosphere in the combustion chamber, fine water droplets included in each emulsion fuel droplet will explode due to the instantaneous vaporization, and smash the emulsion fuel droplet. This is called as the *micro-explosion* of the fuel droplet, which leads to the main advantages of the emulsion combustion as shown below;

(1) The *micro-explosion* of the fuel droplets due to the included water particles promotes the atomization of the fuel particles, namely promotes the mixing of the fuel with the surrounding air. The combustion efficiency can be increased thereby in high temperature combustion chambers; boilers,

forging furnaces, etc.

(2) Owing to the increase in the combustion efficiency in the furnaces and boilers using emulsion fuels, the needed amount of *cold excess air*, which is additionally blown into the furnaces for the complete combustion of fuels, can be reduced dynamically. The residence time of the hot combustion gases in the furnace becomes long accordingly. Heat loss from the furnaces and boilers can be thereby decreased dynamically, which leads to the obvious reduction of fuel consumption.

(3) The amount of soot and particulates in the exhausted gases can be reduced due to the *Water-Gas Reaction* in the high temperature combustion chambers.

(4) Concentration of NO_x in the exhaust gas can be decreased owing to the decrease in the combustion gas temperature.

(5) Owing to the emulsification many kinds of the waste oils, from machine and food, can be recycled as the useful fuels in many forging furnaces and boilers.

For the stable and long running of many emulsion fuel combustors (including boilers and forging furnaces) without any trouble, the following specifications will be needed;

(1) Diameters of water particles in the sprayed each emulsion fuel droplet should be as uniform as possible and less than about 10 μm.

(2) Emulsion should be stable, namely no separation between the base petroleum fuel and the water occurs until the emulsion fuel is transported into the combustors.

(3) The stability of emulsion fuel should not be affected by the changes of the temperature and of the flow rate into the combustors.

(4) In the use of emulsion fuel, there is no corrosion in any parts and devices in combustor.

(5) The amount of the used surface-active agent for emulsification should be as small as possible.

(6) The system of emulsion production is not so expensive.

3. DEVELOPMENT OF EMULSIFIED FUELS

To produce and maintain the stable emulsified fuel there have been some very difficult points; uniform and stable dispersion of insoluble fine water particles in the petroleum fuels, the transportation into combustion chambers or furnaces without any disruption of emulsion state. It is thereby not easy to attain the stable combustion of sprayed emulsion fuel without any trouble for a long running period of many combustors.

Many manufacturers of combustion devices have, therefore, tried to develop and improve the emulsification devices and emulsion combustors for recent over two decades. Almost all the manufacturers have tried to develop the stable emulsion fuels by using the surface-active agent in the mixture of petroleum fuel and water, where the ratio of water in the mixture is 20~40 vol.% or more. Although it is the fact in itself that the emulsified fuels including water can be burned in the laboratory scale combustors, the application of the experimental results to the many kinds of real industrial combustion devices without any trouble is, however, never easy.

Needless to say, the cost of the surface-active agent in emulsion fuel cannot be negligible during the long running period of large-scale combustors, although the needed amount of the surface-active agent is not so large. In addition, the exhaust gases from the combustors will contain the species of the molecules of surface-active agent. It should be noted here that the use of the emulsion fuels that contains too much water could never be a good energy-saving technology owing to the increase in fuel consumption due to the large decrease in the combustion efficiency.

The content of water in the emulsion fuel, therefore, should be determined and controlled appropriately for the kind of base petroleum fuels, and never be increased so much from the point of view of the long and safe running of the combustors (furnaces) without any trouble. The appropriate water content will be less than about 10 vol.% for the emulsified fuels of gas oil and A-heavy oil, and less than about 20 vol.% even for the emulsion of C-heavy oil.

Today, the search of "*Emulsion Fuel*" through the Internet shows us about 300~600 reports, articles and research papers even in Japan. From the point of view of the combustion engineering, however, many random and doubtful reports or articles also can be found.

Who can believe the article where the emulsion fuels of which the water content is 60 vol.% can be used in combustors for long period without any trouble? Who can believe the article that aims finally at *water-combustion* by using the emulsion fuel with ultra high content of water? Needless to say, we have known already that the use of emulsion fuel in boilers, forging furnaces and diesel engines is the excellent combustion technology for energy saving and for prevention of environmental pollution. Among many today's reports, articles and papers concerning the emulsion fuel, we should, therefore, review them strictly and find the real emulsion technologies that satisfy the aforementioned *Needed Specification of Emulsion Fuel*. The present study aims to develop a new mechanical technology of W/O type emulsification of petroleum fuels without any surface-active agents, and to examine the performance of the mechanical emulsifier.

4. GEAR PUMP TYPE EMULSIFIER

An excellent mechanical emulsification device using a kind of gear pumping mechanism consisting of some specified gears has been devised by T.Nakayama since over twenty years ago, which is described in his patent[43]. The mechanical emulsification device has been improved and developed so that it can produce the stable W/O type emulsion fuel mechanically without any surface-active agent.

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 enables also the recycling technology of some waste oils (from machine and food) for the fuels in boilers and many furnaces.

The present study examined experimentally the following subjects:

(1) Stability of the W/O emulsion produced by this device.

(2) Improvement of the emulsification performance of this gear pump type mechanical emulsification device.

Figs.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 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.

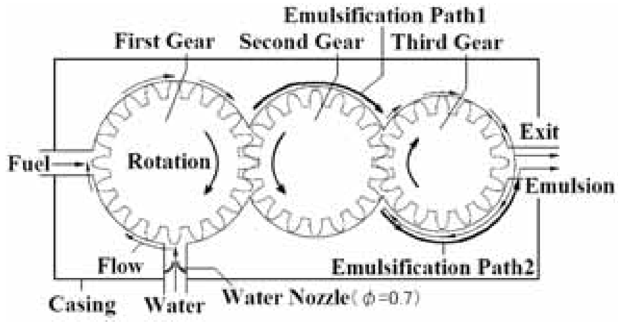

Fig.1 The scheme of top view of mechanical emulsifier (3-gears type) in this study.

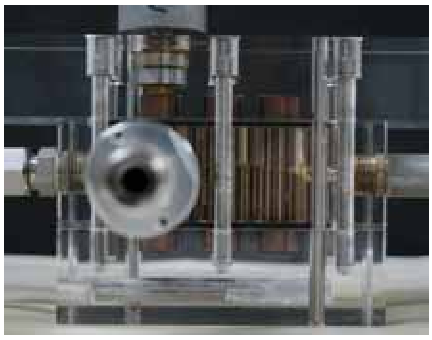

Fig.2 The side view of mechanical emulsifier (3-gears type) in this study.

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.

Fig.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, where 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 gear.

Although the theoretical explanation of this emulsification mechanism is not easy and can not be given in the present stage, it should be noted that there is no other region for the emulsification except the 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.

Aiming to improve the emulsification performance and to increase the discharge from emulsifier, the emulsifier with two gears also has been developed, shown in Figs.5 and 6.

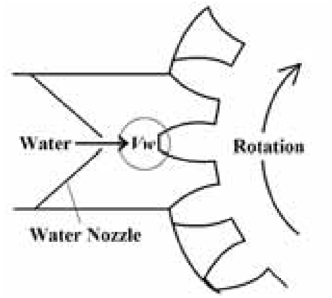

Fig.3 Scheme of the water injection (Velocity: V_w) from the fine exit of nozzle to the first gear for the emulsification.

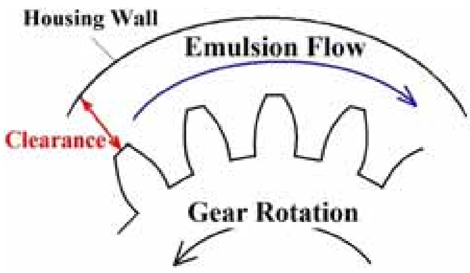

Fig.4 Schematic model of the emulsification region in the clearance between the gear teeth and the housing wall.

This type of emulsifier has a series of the same two gears, where the diameters of the gear tip circle and the pitch circle are 27.5 and 25 mm respectively. The first gear is driven directly by motor at 300~1300 rpm. The teeth length in the axis direction of gear is 60 mm, the module is 1.25, and the number of teeth is 20. The clearance between the first gear tip and the housing wall is about 0.05 mm. The clearance between the second gear tip and the housing wall is 0.4 mm at one side (emulsification path), and about 0.05 mm at the other side.

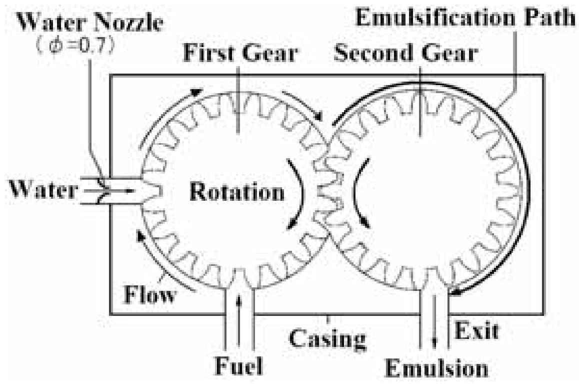

Fig.5 The scheme of top view of mechanical emulsifier (2-gears type) in this study.

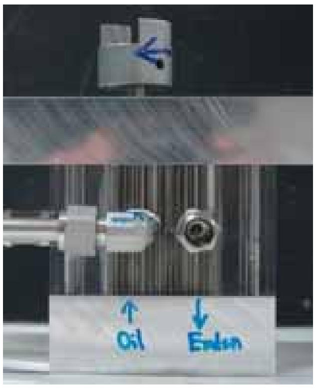

Fig.6 The side view of mechanical emulsifier (2-gears type) in this study.

5. STABILITY OF EMULSIFICATION

A typical W/O emulsified gas oil, where the water content is about 9 vol.% for gas oil is shown in Fig.7. Fig. 8 shows the typical microscopic photograph of this emulsion, where we can confirm many water particles (dispersed small circles) of which the diameters are about 10 μm or less.

A typical W/O emulsified A-heavy oil is shown in Fig.9, where the water content is about 6 vol.% for A-heavy oil. As shown in these photographs, the colors of W/O type emulsified gas oil and A-heavy oil become whitish compared with that of the original fuels.

It should be noted, however, that the present gear pomp type emulsifier should be run in the appropriate condition for the production of stable W/O emulsion. Too much water content and too strong mixing with high revolution of driving gear or both will bring about very unstable emulsion, and often result in the phase inversion from W/O to O/W type, which is shown in Fig.10. The O/W type emulsion due to the phase inversion is non-uniform and unstable (easy to break), which leads to complete disruption of the emulsion. There exist consequently the limiting water content and the limiting revolution of the driving gear for the stable emulsification.

The stability (lifetime) of emulsion was examined by the measurement of the decay of transmittance of laser beam (He-Ne) due to the emulsification.

Fig.11 shows the relation of the relative transmittance of emulsified gas oil; the ratio of the transmittance of laser beam through the emulsion to that through the original gas oil, and the elapsed time from emulsification.

Fig.7 Representative photograph of emulsified gas oil (Water: 9 vol.% for Fuel, 800 rpm).

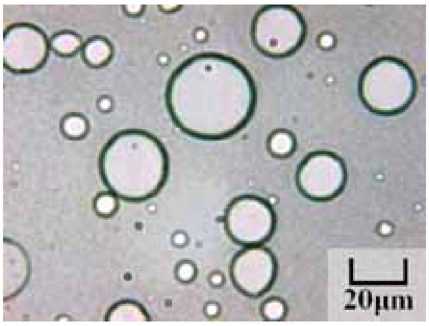

Fig.8 Microscopic photograph of water particles in the emulsified gas oil (Water: 9 vol.% for Fuel, 800 rpm).

Fig.9 Representative photograph of emulsified A-Heavy oil (Water: 6 vol.% for Fuel, 800 rpm).

The low transmittance means stable emulsion, and the increase in the transmittance means the disruption of emulsion; separation of fuel and water. As shown in this figure, the emulsion of gas oil begins to break at about 12 hours after the emulsification, and reaches complete disruption after about 36 hours.

Fig.12 shows the relation between the time for beginning of the disruption of A-heavy oil emulsion and the revolution of the driving (the first) gear, where the disruption was determined as the separation of a half amount of water.

Fig.10 Representative photograph of O/W type emulsified gas oil due to the phase inversion from W/O type.

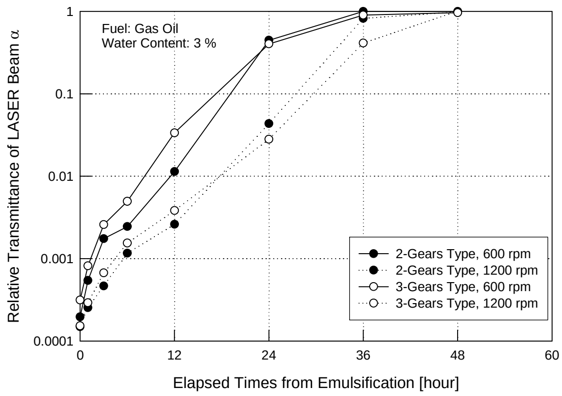

Fig.11 Relative transmittance of laser beam through the emulsified gas oil.

As shown in this figure, the increase in the revolution of emulsifier enhances the stability of emulsion, which may be due to the strong mixing in the emulsification path. The cross of the lines in this figure may be due to the difference of the clearance in the emulsification path of the emulsifier.

Fig.13 shows the relation of the limit (permissible) of water content in the emulsion (Gas oil and A-heavy oil) and the revolution of driving gear of emulsifier (2-gears type), where the limiting water content was determined as the maximum water content which can sustain the uniform and high stable emulsion for at least 30 seconds after the discharge from emulsifier, and the phase inversion (from W/O to O/W) does not occur. As shown in this figure, the water contents in the emulsions of A-heavy oil and Gas oil should be less than 20 vol.% and 4 vol.% respectively if these emulsion fuels are transported directly (without reserve tank) from this emulsifier to the combustor.

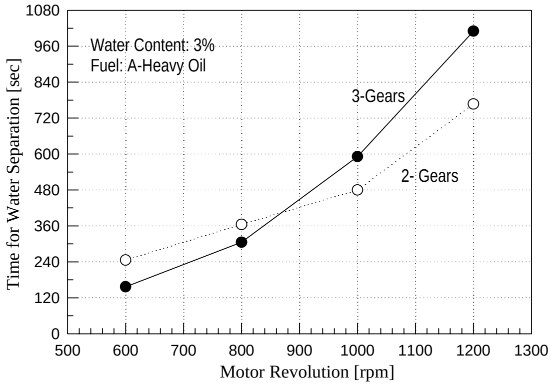

Fig.12 Relation between the time of beginning of disruption (separation) of A-heavy oil emulsion (water; 3 vol.%) and the revolution of the driving (the first) gear of emulsifier with 2 and 3 gears

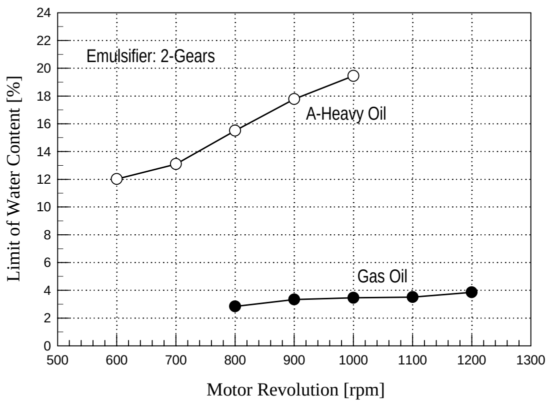

Fig.13 Relation of the limiting (permissible) water content in the emulsion (Gas oil and A-heavy oil) and the revolution of driving gear of emulsifier with 2-gears.

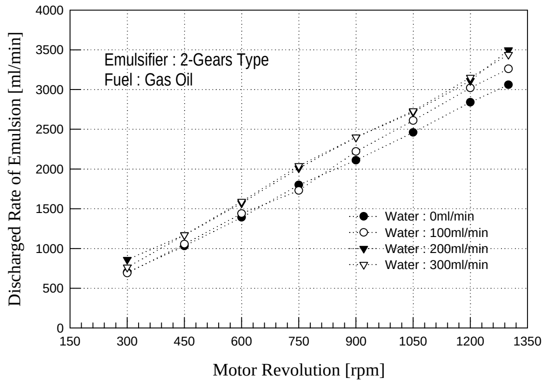

Fig.14 Discharge rate of emulsified gas oil from 2-gears type emulsifier.

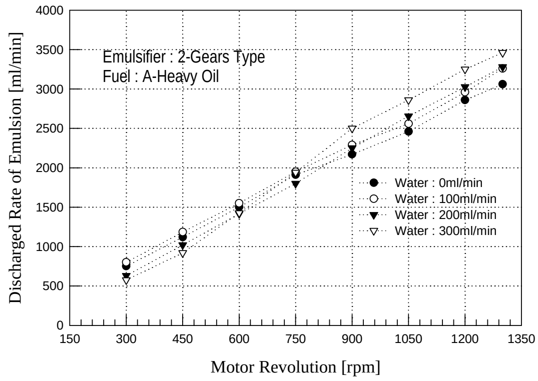

Fig.15 Discharge rate of emulsified A-heavy oil from 2-gears type emulsifier.

6. DISCHARGE PERFORMANCE

Figs.14 and 15 show the discharge rate of emulsions of gas oil and of A-heavy oil at each revolution of the driving gear of emulsifier.

As shown in the result, we can see no obvious difference due to the water content and to the fuel, although the difference in the viscosity of emulsion due to the change of water content may affect the discharge rate of gear pump type emulsifier.

7. EFFECT OF INLET PORT ORDER ON THE EMULSIFICATION

Since the high-speed water injection toward the driving gear will enhance the emulsification effect in the present emulsifier, we can infer that the order of inlet ports of fuel and water also has some noticeable effect on the stability of emulsion.

Fig.16 shows the effect of the order of inlet ports of fuel and water of the 3-gears type emulsifier (shown in Fig.1) on the time of disruption (the separation of a half amount of water, as shown in Fig.12). In the result, we can see a noticeable increase in the stability of emulsion when the water injection is the first and the fuel suction is the second. Although the clear explanation for this result can not be given in the presents stage, the emulsification effect due to high-speed water jet near the driving gear before the inlet of fuel may bring about it.

It should be noted also that the distribution range of water jet toward the driving gear will have a noticeable effect on the emulsification in particular for the emulsifier with large gears. Fig.17 shows the effect of divergence of the water inlet; jet from the single fine hole (ϕ 0.7) of nozzle and that without nozzle, toward the driving gear on the time of disruption (the separation of a half amount of water, as shown in Fig.12) for 2-gears type emulsifier (the teeth length in the axis direction of gear is 60 mm).

In the result, we can see a noticeable increase in the stability of emulsion owing to the wide divergence of water without nozzle. Consequently, multi directional and wide range water injection toward the driving gear will be needed for the emulsifier with large gears.

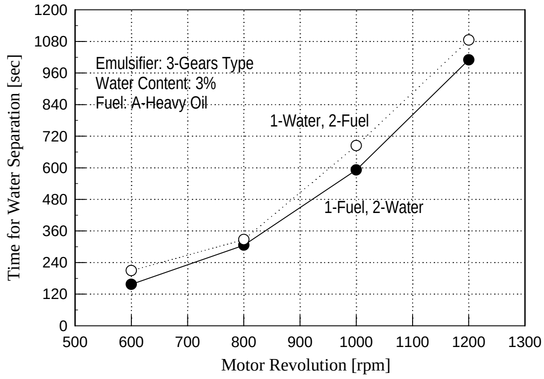

Fig.16 Effect of the order of inlet ports of fuel and water on the time for water separation.

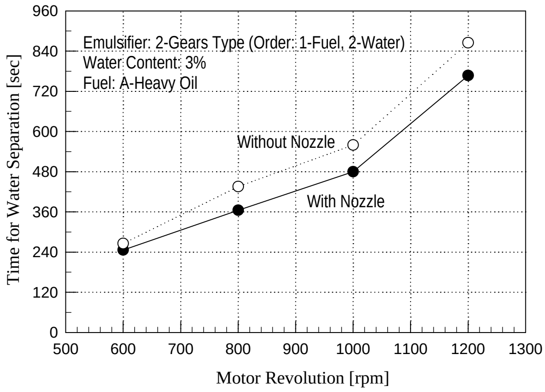

Fig.17 Effect of the distribution of water injection to the driving gear on the stability of emulsion.

8. CONCLUDING REMARKS

The present gear pump type mechanical emulsifier is able to produce the stable W/O type emulsions of gas oil and of A-heavy oil without surface-active agent. The present study revealed some interesting and important characteristics in the emulsification process of the gear pump type mechanical emulsifier as follows;

(1) The narrow clearance and the long path length between the second gear tip and the housing wall will increase the stability of emulsion although they decrease the discharge rate from emulsifier.

(2) There are some limiting conditions in the water content and in the revolution of the driving gear for the prevention of phase inversion from W/O to O/W type emulsion.

(3) The water content in the emulsions of A-heavy oil and of gas oil should be less than 20 vol.% and 4 vol.% respectively if they are transported directly (without reserve tank) from this emulsifier to the combustor.

(4) The order of inlet ports of water and of fuel, and the initial diverging water jet toward the first gear will have a noticeable effect on the stability of emulsion.

ACKNOWLEDGEMENTS

The authors would like to express their 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. A.Hoshino, H.Inotume and A.Kamiyama are appreciated also for their great help in conducting the experiment. The authors are indebted for the financial support by Nissan Science Foundation and Yamaguchi Scholarship 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) Petroleum 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) Petroleum 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 Petroleum 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/*N_2H_4 *Droplets at Weightless and Free falling Conditions*, Comb. Sci. and Tech., Vol. 44, pp. 289-306, 1986.
23) Randrolph, 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).