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EXPERIMENTAL INVESTIGATION ON EFFECT OF MINIMUM QUANTITY LUBRICATION (MQL) IN MACHINING STEEL

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ABSTRACT

Application of cutting fluids changes the performance of machining operations because of their lubrication, cooling, and chip flushing functions. In the machining of hardened steel materials, no cutting fluid is applied in the interest of low cutting forces and low environmental impacts. Minimum quantity lubrication (MQL) presents itself as a viable alternative for turning with respect to tool wear, heat dissertation, and machined surface quality. This study compares the mechanical performance of minimum quantity lubrication to completely dry lubrication for the turning of steel based on experimental measurement of cutting temperature, chip reduction coefficient, chip shape and color, surface finish and dimensional deviation. Results indicated that the use of near dry lubrication leads to lower cutting temperature, favorable chip-tool interaction, reduced surface roughness and dimensional deviation.

1. INTRODUCTION

High production machining of steel inherently generates high cutting zone temperature. Such high temperature causes dimensional deviation and premature failure of cutting tools. It also impairs the surface integrity of the product by inducing tensile residual stresses and surface and subsurface microcracks in addition to rapid oxidation and corrosion [1,2]. In high speed machining, conventional cutting fluid application fails to penetrate the chip-tool interface and thus cannot remove heat effectively [3,4]. Addition of extreme pressure additives in the cutting fluids does not ensure penetration of coolant at the chip-tool interface to provide lubrication and cooling [5]. However, high-pressure jet of soluble oil, when applied at the chip-tool interface, could reduce cutting temperature and improve tool life to some extent [6,7].

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However, the advantages caused by the cutting fluids have been questioned lately, due to the several negative effects they cause. When inappropriately handled, cutting fluids may damage soil and water resources, causing serious loss to the environment. Therefore, the handling and disposal of cutting fluids must obey rigid rules of environmental protection. On the shop floor, the machine operators may be affected by the bad effects of cutting fluids, such as by skin and breathing problems [8,9].

For the companies, the costs related to cutting fluids represent a large amount of the total machining costs. Several research workers [10,11] state that the costs related to cutting fluids are frequently higher than those related to cutting tools. Consequently, elimination on the use of cutting fluids, if possible, can be a significant economic incentive. Considering the high cost associated with the use of cutting fluids and projected escalating costs when the stricter environmental laws are enforced, the choice seems obvious. Because of them some alternatives has been sought to minimize or even avoid the use of cutting fluid in machining operations. Some of these alternatives are dry machining and machining with minimum quantity lubrication (MQL).

Dry machining is now of great interest and actually, they meet with success in the field of environmentally friendly manufacturing [10,12]. In reality, however, they are sometimes less effective when higher machining efficiency, better surface finish quality and severer cutting conditions are required. For these situations, semi-dry operations utilizing very small amounts of cutting lubricants are expected to become a powerful tool and, in fact, they already play a significant role in a number of practical applications [13-17]. Minimum quantity lubrication (MQL) refers to the use of cutting fluids of only a minute amount-typically of a flow rate of 50 to 500 ml/hour which is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition. The concept of minimum quantity lubrication, sometimes referred to as near dry lubrication [10] or micro-lubrication [18], has been suggested since a decade ago as a means of addressing the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting fluid particles on factory shop floors. The minimization of cutting fluid also leads to economical benefits by way of saving lubricant costs and workpiece/tool/ machine cleaning cycle time.

Significant progress has been made in dry and semidry machining recently, and minimum quantity lubrication (MQL) machining in particular has been accepted as a successful semidry application because of its environmentally friendly characteristics. Some good results have been obtained with this technique [19]. Lugscheider et al. [20] used this technique in reaming process of gray cast iron and aluminum alloy with coated carbide tools and concluded that it caused a reduction of tool wear when compared with the completely dry process and, consequently, an improvement in the surface quality of the holes. Dhar et al. [21] also used this technique in turning process of medium carbon steel and concluded that, in some cases, a mixture of air and soluble oil has been shown to be better than the overhead flooding application of soluble oil.

The drilling of aluminum-silicon alloys is one of those processes where dry cutting is impossible [22] due to the high ductility of the workpiece material. Without cooling and lubrication, the chip sticks to the tool and breaks it in a very short cutting time. Therefore, in this process a good alternative is the use of the MQL technique [23, 24].

The review of the literature suggests that minimum quantity lubrication provides several benefits in machining. The main objective of the present work is to experimentally investigate the role of minimum quantity lubrication on cutting temperature, chip formation mode, surface finish and product quality in machining C-60 steel at industrial speed-feed condition by coated carbide insert (SNMM 120408-PM) as compared to completely dry machining.

2. EXPERIMENTAL INVESTIGATIONS

For the present experimental studies, C-60 steel (φ125 X 760 mm) was turned in a high power rigid lathe (USA, 15hp) by coated carbide insert (SNMM 120408-PM) at industrial speed-feed combinations under both dry and MQL conditions. The experimental conditions are given in Table-1. The ranges of the cutting velocity (V_c) and feed rate (S_o) were selected based on the tool manufacturer's recommendation and industrial practices. Depth of cut, being less significant parameter, was kept fixed.

Table-1 Experimental conditions

Machine tool	: High power rigid lathe, USA, 15 hp
Workpiece	: C-60 steel (φ125 X 760 mm) (Hardness 195 BHN)
Cutting tool	: SNMM 120408-PM (SC-4025, Drillco)
Coating	: TiCN + Al_2O_3
Tool holder	: PSBNR 2525M12, Drillco
Tool geometry	: -6, -6, 6, 6, 15, 75, 0.8 (mm)
Process parameters	
Cutting velocity, V_c	: 72, 94, 139 and 164 m/min
Feed rate, S_o	: 0.10, 0.13, 0.16 and 0.20 mm/rev
Depth of cut, t	: 1.5 mm
Environment	: Dry and Minimum Quantity Lubrication

The MQL needs to be supply at high pressure and impinged at high speed through the nozzle at the cutting zone. Considering the conditions required for the present research work and uninterrupted supply of MQL at constant pressure around 3.5 bar over a reasonably long cut, a MQL delivery system has been designed, fabricated and used. The schematic view of the MQL set up is shown in Figure 1. In this system, a compressor is used to supply high-pressure air (3.5 bar) and the fluid pump supplies the cutting fluid from the fluid reservoir. This high pressure-air from the compressor enters into two chambers. One is fluid chamber and another is mixing chamber. The fluid chamber is connected at the bottom with the mixing chamber by a nipple. A needle is inserted in the nipple by a rubber pad to permit a little amount of fluid flow under high pressure. The compressed air through the upper inlet port creates the pressure to cause the fluid to go to the mixing chamber.

The mixing chamber has two-inlet port and one outlet port. One of the inlet ports permits high-pressure compressed air to the mixing chamber. The flow of this compressed air is controlled by a globe valve and measured by a pressure gauge. The other port permits fluid flow from the fluid chamber. The air and the cutting fluid are mixed in the mixing chamber so that the mixture of cutting fluid and air is impinged at a high speed through the nozzle at the chip-tool interface (Figure 1). Minimum quality lubrication jet was impinged from a specially designed nozzle to cool the tool and the work material at the hot cutting zone. The thin but high velocity stream of MQL was projected along the auxiliary cutting edge of the insert, so that the coolant reaches as close to the chip-tool and the work-tool interfaces as possible. The photographic view of the experimental set-up is shown in Figure 2.

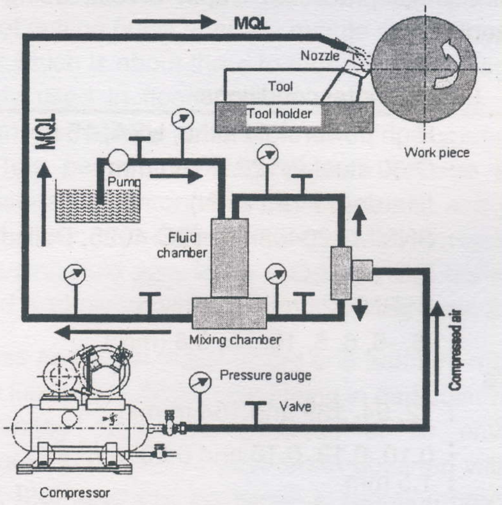

Figure 1: Schematic view of MQL unit

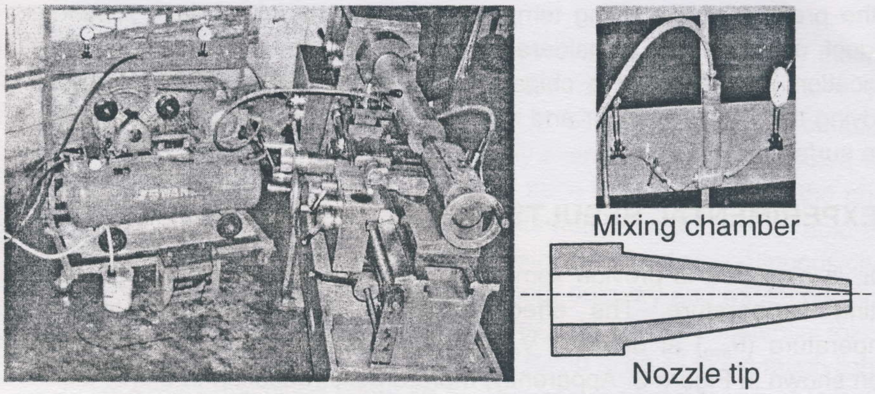

Figure2: Photographic view of the experimental set-up

MQL is expected to provide some favorable effects mainly through reduction in cutting temperature. The simple but reliable tool-work thermocouple technique [25] has been employed to measure the average cutting temperature during turning at different V_c-S_o combinations by the coated carbide insert under dry and MQL conditions. For the present investigation, the calibration of the work-tool thermocouple has been carried out by external flame heating. The work-tool thermocouple junction was constructed using a long continuous chip of the concerned work material and a tungsten carbide insert to be used in actual cutting. To avoid generation of parasitic emf, a long carbide rod was used to extend the insert. A standard K-type thermocouple is mounted at the site of tool-work junction. The oxy-acetylene torch simulated the heat generation phenomena in machining and raised the temperature at the chip-tool interface. Standard thermocouple directly monitored the junction temperature when the emf generated by the hot junction of the chip-tool was monitored by a digital multimeter.

The effectiveness, efficiency and overall economy of machining any work material by given tools depend largely only on the machinability characteristics of the tool-work materials under the recommended condition. Machinability is usually judged by

i. cutting temperature which affect product quality and cutting tool performance
ii. pattern and mode of chip formation
iii. magnitude of the cutting forces which affects power requirement, dimensional accuracy and vibration
iv. surface finish and
v. tool wear and tool life

In the present work, cutting temperature, chip pattern, surface roughness and product accuracy are considered for studying the role of minimum quantity lubrication. The machining chips were collected during all the treatments for studying their shape, colour and nature of interaction with the cutting insert at its rake surface.

3. EXPERIMENTAL RESULTS AND DISCUSSION

MQL is expected to provide some favorable effects mainly through reduction in cutting temperature. The effect of MQL on average chip-tool interface temperature (θ_{avg}) at different V_c and S_o under dry and MQL conditions have been shown in Figure 3. Apparently, more drastic reduction in θ_{avg} is expected by employing MQL but actually it is not so because the MQL could not reach the intimate chip-tool contact zone. However, during machining at lower V_c when the chip-tool contact is partially elastic, where the chip leaves the tool, MQL is dragged in that elastic contact zone in small quantity by capillary effect and is likely to enable more effective cooling. With the increase in V_C the chip makes fully plastic or bulk contact with the tool rake surface and prevents any fluid from entering into the hot chip-tool interface. MQL cooling effect also improved to some extent with the decrease in feed particularly at lower cutting velocity. Possibly, the thinner chips, specially at lower chip velocity, are slightly pushed up by the MQL jet coming from opposite direction and enables it come closer to the hot chip–tool contact zone to remove heat more effectively. Further, at high velocity, the coolant may not get enough time to remove the heat accumulated at the cutting zone resulting in less reduction in temperature under MQL condition at high cutting velocity. However, it was observed that the MQL jet in its present way of application enabled reduction of the average cutting temperature by about 5 to 10% depending upon the levels of the process parameters, V_c and S_o. Even such apparently small reduction in the cutting temperature is expected to have some favourable influence on other machinability indices.

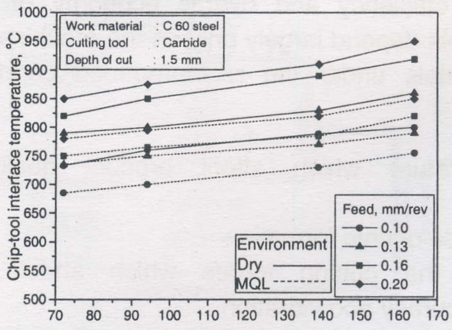

Figure 3: Variation in average chip-tool interface temperature with V_c at different S_o under dry and MQL conditions.

The form, colour and thickness of the chips also directly and indirectly indicate the nature of chip-tool interaction influenced by the machining environment. The chip samples collected while turning the steel at different V_c-S_o combinations under dry and MQL conditions have been visually examined and categorized with respect to their shape and colour. The result of such categorization of the chips produced at different conditions and environments has been shown in Table-2. It appears from Table-2 that the insert produced mostly spiral and discontinuous chips almost throughout the V_c-S_o range undertaken under both dry and MQL conditions expectedly for the presence of deep parallel grooves, which have substantial role on chip pattern. However, the colour of the chips was found to be all along much lighter when the material was machined under MQL. This has occurred reasonably due to reduction in the cutting zone temperature followed by bulk cooling of the outgoing chips by minimum quantity lubrication.

Table-2 Shape and colour of chips at different V_c and S_o

Feed rate, S_o (mm/rev)	Cutting velocity V_c (m/min)	Environment			
		Dry		MQL	
		Shape	Colour	Shape	Colour
0.10	72	half turn	burnt blue	half turn	metallic
	94	spiral	blue	half turn	metallic
	139	spiral	golden	spiral	metallic
	164	spiral	golden	spiral	metallic
0.13	72	spiral	burnt blue	spiral	metallic
	94	half turn	burnt blue	spiral	metallic
	139	spiral	burnt blue	half turn	metallic
	164	half turn	burnt blue	half turn	metallic
0.16	72	half turn	burnt blue	half turn	metallic
	94	half turn	burnt blue	half turn	metallic
	139	half turn	burnt blue	half turn	metallic
	164	half turn	burnt blue	half turn	metallic
0.20	72	spiral	burnt blue	half turn	metallic
	94	spiral	burnt blue	half turn	metallic
	139	spiral	burnt blue	half turn	metallic
	164	spiral	burnt blue	half turn	metallic

Another important machinability index is chip reduction coefficient, ζ (ratio of chip thickness after and before cut). For given cutting conditions, the value of ζ depends upon the nature of chip-tool interaction, chip contact length and chip form all of which are expected to be influenced by MQL in addition to the levels of V_c and S_o. The variation in value of ζ with V_c and S_o as well as machining environment have been plotted and shown in Figure 4.

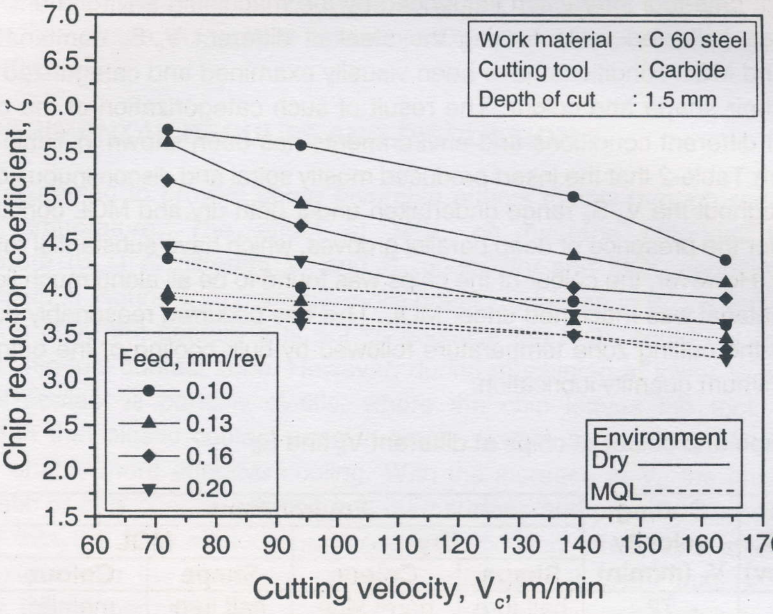

Figure 4: Variation in ζ with cutting velocity at different feed rates under dry, wet and MQL conditions.

Figure 4 clearly shows that throughout the present experimental domain the value of ζ gradually decreased with the increase in V_c though in different degree for the different tool-work combinations, under both dry and MQL conditions. The value of ζ usually decreases with the increase in V_c particularly at its lower range due to plasticization and shrinkage of the shear zone for reduction in friction and built-up edge formation at the chip-tool interface due to increase in temperature and sliding velocity. In machining steel by carbide tool, usually the possibility of built-up edge formation and size and strength of the built-up edge, if formed gradually increase with the increase in temperature due to increase in V_c and also S_o and then decrease with the further increase in V_c due to too much softening of the chip material and its removal by high sliding speed. Figure 4 also shows that MQL has reduced the value of ζ particularly at lower values of V_c and S_o. By MQL applications, ζ is reasonably expected to decrease for reduction in friction at the chip-tool interface and reduction in deterioration of effective rake angle by built-up edge formation and wear at the cutting edges mainly due to reduction in cutting temperature.

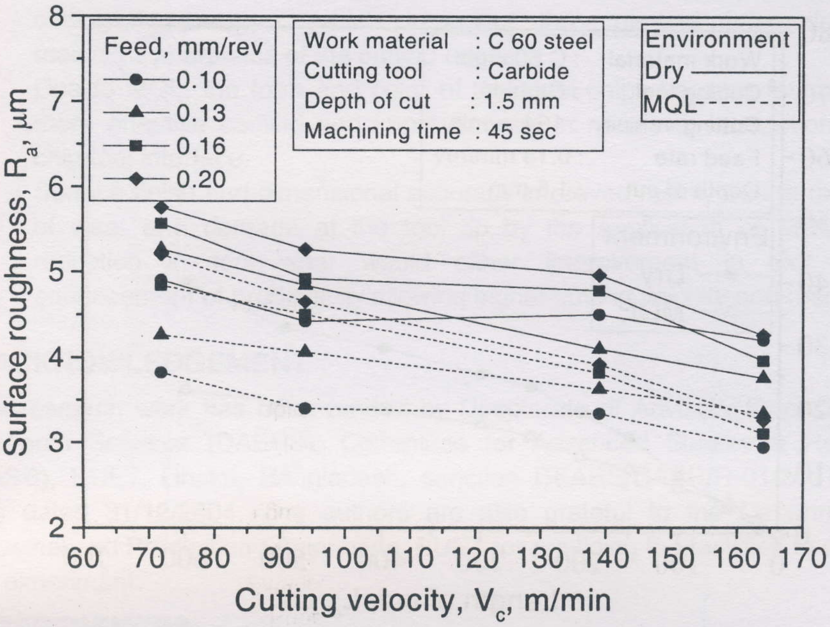

Figure 5: Variation in roughness with cutting velocity at different feed rates under dry and MQL conditions.

Surface roughness is another important index of machinability, which is substantially influenced by the machining environment for given tool-work pair and speed-feed combinations. Surface roughness has been measured after a few seconds of machining with sharp tool while recording the chip-tool interface temperature. The surface roughness attained after 45 seconds of machining of steel at various V_c-S_o combinations under dry and MQL conditions is shown in Figure 5. Figure 5 clearly shows that surface roughness as such increased with the increase in feed and decreased with the increase in V_c. Reduction in roughness with the increase in V_c may be attributed to smoother chip-tool interface with lesser chance of built-up edge formation in addition to possible truncation of the feed marks and slight flattening of the tool-tip. Increase in V_c may also cause slight smoothing of the abraded auxiliary cutting edge by adhesion and diffusion type wear and thus reduced surface roughness. It is evident in Figure 5 that MQL could provide marginal improvement in surface finish at the beginning of machining with the fresh cutting edge. The slight improvement in surface finish by MQL might be due to reduction in break-in wear and also possibly reduction or prevention of built-up-edge formation.

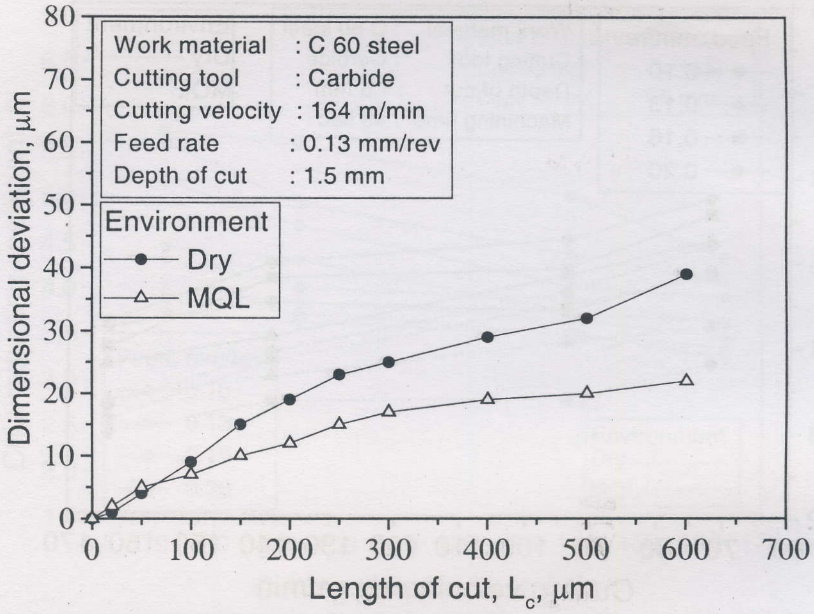

Figure 6: Variation in change in dimension with cutting length under dry and MQL conditions

Figure 6 shows the effect of MQL on the dimensional accuracy of the turned job. MQL provided better dimensional accuracy in respect of controlling the increase in diameter of the finished job with machining time. The finished job diameter generally deviates from its desired value with the progress of machining, i.e. along the job-length mainly for change in the effective depth of cut due to several reasons which include wear of the tool nose, over all compliance of the machine-fixture-tool-work system and thermal expansion of the job during machining followed by cooling. Therefore, if the machine-fixture-tool-work system is rigid, variation in diameter would be governed mainly by the heat and cutting temperature. With the increase in temperature the rate of growth of auxiliary flank wear and thermal expansion of the job will increase. MQL takes away the major portion of heat and reduces the temperature resulting decrease in dimensional deviation desirably.

4. CONCLUSIONS

Based on the results of the present experimental investigation the following conclusions can be drawn:

- The cutting performance of MQL machining is better than that of dry machining because MQL provides the benefits mainly by reducing the cutting temperature, which improves the chip-tool interaction and maintains sharpness of the cutting edges.
- Due to MQL, the form and color of the steel chips became favorable for more effective cooling and improvements in nature of interaction at the chip-tool interface.
- Surface finish and dimensional accuracy improved mainly due to reduction of wear and damage at the tool tip by the application of MQL. Such reduction in tool wear would either improvement in tool life or enhancement of productivity allowing higher cutting velocity and feed.

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DROPLET COMBUSTION WITH LIQUID PARAFFIN AND OXYGENATED FUELS

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ABSTRACT

In this report single liquid fuel droplet combustion of neat diesel fuel, neat oxygenated fuels, blends of diesel-paraffin and diesel-oxygenated fuels have been investigated. The volumetric blending ratios of paraffin and oxygenated fuels to diesel fuel have been set to 0, 25, 50 and 100%. The result showed that the shapes and sizes of the flames of diesel-paraffin and diesel-oxygenate fuel blends were completely different from those of conventional diesel fuel. It has been interesting to note that the combustion with the blends of diesel-paraffin and diesel-oxygenate ended rapidly after the ignition started. Compared with neat diesel fuel, the combustion speed was found faster for low temperature paraffin fuels including normal nonane (NN) and normal decane (ND) as well as oxygenated fuels, such as, ethylene glycol mono n butyl ether (ENB) and diethyl succinate (DES). The rapid changes of combustion might result from the micro-explosion of the fuel droplet for their low boiling temperature.

1. INTRODUCTION

Combustion of a liquid fuel droplet cloud occurs in a wide range of industrial applications like internal combustion engines, the burners, etc. Several researches have been conducted regarding the fiber-supported fuel droplet combustion (FSDC) to obtain combustion mechanism of a fuel droplet cloud. In a joint program involving California University and Lewis microgravity research center (1), the combustion of liquid fuel droplets having initial diameters between about 1 mm and 6 mm was being studied. The objectives of the work were to improve fundamental knowledge of droplet combustion dynamics through experiments and theoretical analyses. Emphasis of the Princeton work were on the study of simple alcohols (methanol/ethanol), alcohol/water mixtures, and pure alkanes (n-heptane, n-decane) as fuels, with time dependent measurements of drop size, flame stand-off, liquid phase composition and finally, extinction (2-3).

The results from methanol/water droplet combustion experiments conducted FSDC-1 and FSDC-2 were analyzed and compared against the predictions of a detailed numerical model (4). The model used was fully time dependent, with consideration of detailed methanol oxidation chemistry, non-luminous radiative coupling, and water dissolution and vaporization from the liquid phase.

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