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STUDY ON THE CHARACTERISTICS OF HYBRID LUBRI-COOLING USING CFD ANALYSIS

MD RAHATUZZAMAN RAHAT[1] & GUOLONG ZHAO[2]

[1&2]*College of Mechanical and Electrical Engineering Nanjing University of Aeronautics and Astronautics, Nanjing 210009, China*

ABSTRACT

An investigation of the mass flow rate and pressure parameters of a hybrid water-based nanofluid minimum amount lubrication and cryogenic lubrication/cooling liquid nitrogen system is carried out by means of a computational study.The atomization in turbulent conditions was simulated with the help of a fluent-based fluent solver (CFD) through the use of a discrete phase model (DPM). Here, liquid nitrogen serves as a distinct medium for the nano lubricant. Under various input circumstances, the velocity of the jet mist and the droplet sizes of the spray were measured in order to ascertain the coolant mass flow rate and pressure that would yield the most favorable outcomes. To authenticate the current simulation findings, additional coolant/lubricant simulation data were taken into account. It has been shown that droplets of medium size (about 16.05 µm) and greater pressure can efficiently lubricate the working zone.

Keywords: CFD, droplet size, Hybrid lubri-cooling, velocity.

INTRODUCTION

Cryogenic machining (CM) is a new process that has become more popular because it is good for the environment and the economy. It has changed into a long-term process that gives new chances to make products that work better[1]. Nitrogen(N_2) and carbon dioxide(CO_2) are the two cryogens that are used most often in machining.In nature, there is a lot of nitrogen, which makes up 79% of the air[2]. Because it is less dense than air and returns to space after use, less effort is required to clean and dispose of it after machining. Also, it does not pollute the air, endanger the health of the operator, or cause damage to the natural environment. This makes it the most common material used in cryogenic machining[3]. To optimize the machining process, cryogenic gases are injected directly into the cutting zone.It is also clean, doesn't endanger the health of the operator, and doesn't cause any damage to the environment.

The most common cryogenic fluids areLN_2, LOX, $CO_2$and LH_2 The scientific literature has several success stories, most of which compare cryogenic cooling with dry or flood machining. Cryogenic machining has been discussed in depth, although the first notable references date back more than 15 years. Utilizing liquid nitrogen cryogenic cooling, Ti-6Al-4V turning was performed [4]. In comparison to flood machining, the temperature during cutting of this material was brought down to below 500 degrees Celsius, and the cutting velocity was significantly increased. These scientists also presented articles on the lubricating characteristics of LN_2 [5]. According to the author [6], the amount of injection hydrostatic pressure has a considerable effect on the properties of the LN_2 lubricant.The most effective application of the cryogenic gas is at the cutting zone.Similarly, [7] and [8] concluded that increasing the pressure is more effective than increasing the flow rate in cooling down tools. Turning Ti-6Al-4V in liquid nitrogen extended the tool life and reduced wear by around 40%, and by around 30% while machining other titanium alloys [9], [10]. It's not uncommon for authors to employ many approaches or develop novel high-tech lubrication systems. Similarly, two different oil microparticle flow rates are studied in conjunction with supercritical carbon dioxide ($scCO_2$)[11]. To machine with $scCO_2$, one must take use of the unique properties of $scCO_2$, one of which is its potential ability to dissolve oil. Liquid carbon dioxide is introduced to soy oil in a pressurized tank.Triple point pressure is reached when CO2 dissolves oil, and the resulting mixture is pushed over the cutting zone. For the first time, numerous authors have identified a way to convert Inconel 718 without increasing the tool's temperature or subjecting it to undue mechanical stress by using liquid nitrogen (LN_2) and MQL oil microparticles [12].(MQL) technologies have attracted increasing interest from the academic community and business sector in recent decades due to their low environmental impact.In machining processes, oil-based MQL has been shown in previous research to be a practical substitute for the flood cooling condition, with benefits including less tool wear and improved surface smoothness. In contrast, Toeliminate cutting heat within the machining zone, MQL primarily makes use of the turbulence of compressed air and, to a lesser extent, the condensation of aerosol spray, decreasing its cooling capacity and limiting its application in the processing of tough materials. Adding nanoparticles to a base oil produces a nMQL, which improves both the lubricating and cooling properties of the oil, is one of the most effective techniques[13],The Al_2O_3 nano-lubricant MQL reduced cutting temperature and improved tool wear as well as surface quality compared to the vegetable oil lubrication MQL.According to [14], Electrostatically assisted lubrication methods send fine, regulated oil mists to the machining zone, improving performance and reducing oil mist concentration., The usage of electrostatically assisted lubricantsmethods supply fine, controlled oil mists to the machining zone to increase efficiency while decreasing oil mist concentration.

For the MQL and cryogenic machining systems, computational fluid dynamics (CFD) has shown to be a useful tool for gathering detailed data and flow visualization that conventional testing cannot provide. CFD simulations of cryogenic coolant inside the milling tool's reduced shape were reported. Cryogenic flow behavior inside pipes with varying geometries and flow characteristics may be studied using numerical simulation. Arunachalam et al. developed a predictive model for cooling system spray Sauter Mean Diameter(SMD). Researchers found that the method may be used to calculate an optimal spray input parameter range for MQL. [15]. The reason in which MQL use improved surface smoothness was by decreasing erosion rate and damage at the tip of the tool.Tawakoli et al. investigated how atomizing air pressure and flow rate affected grinding accuracy and found that nozzle position was significant[16]. Again, CFD is used to simulate a standard MQL nozzle and investigate its flow pattern. The results of their study demonstrated the flow distribution at the nozzle's tip at a certain pressure, which provided valuable insight into the nozzle's final form.According to the literature review, CFD modelling is needed to determine how nozzle placement affects MQL spray immersion and how air pressure and mass flow rate affect wettability region and MQL efficiency. Toshiyuki et al. used CFD to improve superalloy finish-turning oil mist spraying. They found that oil droplet flight determines its distance, and tiny particles are inadequate for MQL machining. Spraying the cutting spot obliquely enhances cooling and lubrication. Coolant computational analysis is infrequently researched despite many cryogenic cooling studies.

The primary goal of this research is to get a CFD analysis of the hybrid lubri-cooling spray characteristics such as droplet size distribution and hybrid lubri-coolant velocity at various mass flow rates and pressures. The droplet size of the spray is very important in machining. The medium-sized droplet with increased pressure can adequately lubricate the tool-chip contact. While machining, medium sized droplet can provide excellent lubrication, minimize cutting forces, and improve surface smoothness.

IMPACT OF FLOW RATE AND PRESSURE ON DROPLET SIZE

During the lubricating process, the droplet size plays a significant role. The pressure, spray properties, and mass flow rate all have a substantial bearing on the outcome. The volume of a particle and the quantity of droplets that are produced as mist per second are the two factors that combine to determine the saturated area of a spray. Based on Radoslaw et al., when

MQL flow rate increases, droplet size decreases, resulting in an increase in droplet number [10]. Increased pressure as well as mass flow improve wetting area, which is advantageous to the machining process. Lubrication should thoroughly cover the work-tool interface for the optimum results.When the mist is expelled from the nozzle, it contains droplets of spherical size that have a diameter of D and a velocity of V, the effect of gravity is not considered, has a disposition distance x

$$x = \frac{\rho \Delta V D^2}{18\eta C}\left(\frac{\rho-\rho_a}{\rho}\right) \tag{1}$$

Where ρ is droplet density, η is the nano lubricant's viscosity. There's a drag coefficient in the air for the moving droplet which is [2]:

$$C = \frac{\pi\left(4+4R+{}^{4}/_{3}R^2+\frac{1}{6}R^3+{}^{2}/_{3}e^R(R-6)\right)}{2(R+1)+e^R(R^2-2)} \tag{2}$$

where

$$R = \frac{\rho \Delta V D}{\eta} \tag{3}$$

Bigger droplets, which have higher inertia, have a greater chance of falling early and failing to travel enough to wet the work tool contact. Likewise, smaller droplets have a greater chance of failing to reach the work area and provide adequate lubrication. As a result, middle-sized droplets are the optimum choice for better working zone penetration and wettability.

NUMERICAL MODELING AND SIMULATION

When compared to dry machining and flood cooling, MQL is clearly the superior method. When it comes to MQL efficiency, droplet size is a major factor. The quality of MQL is determined by variables such droplet velocity, pressure, and diameter, however only a limited number of research have focused on this topic. So, the primary purpose of this work is to use Computational Fluid Dynamics (CFD) to simulate oil mist atomization, investigate the effect of spray settings, and evaluate the results alongside those obtained with alternative lubricants. One of the major drawbacks of machining is the difficulty in getting cutting fluid (lubrication) to the tool-work interface. While milling, the issue is made worse by the use of a pressure belt around the tool. With multi-quadratic atomization, the lubricant can be sprayed in smaller, more manageable droplets, making it more convenient to use. This paper makes use of the FLUENT flow solver and a Computational Fluid Dynamics (CFD) model to examine mist atomization. The variables being considered are flow rate and pressure. Using a turbulent flow discrete phase model (DPM), we modelled the atomization of a mist in liquid nitrogen, with the nan lubricant serving as the discrete phase medium.

A. Modeling nozzle

The nozzle was developed using the manufacturer's specs (Spraying System Co., USA). The 2D model of the nozzle was created in Gambit 2.4.6, and modeling and grid partitioning were performed. Because the real stand of distance was 100 mm, a virtual box with dimensions of 100 mm×100 mm was generated.

To investigate the behaviour of air droplets, a gap of 100 mm has been set between both the tool and also the nozzle. The simulation is a near-perfect representation of the actual process because all of the manufacturer-provided nozzle dimensions were employed. The complete 2D model needs to be cut up into thirds. The environment, the mixing zone, and the stream of liquid nitrogen and nano lubricant make up the three parts. Figure 1 displays the Gambit 2.3.16 grid-partitioned and boundary-constrained 2D model.

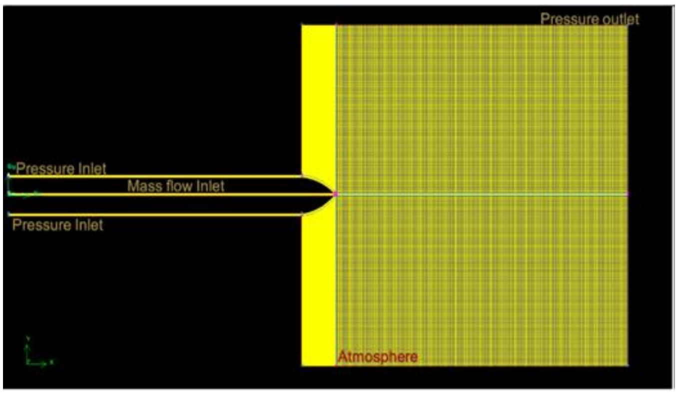

Figure 1: Mesh and Boundary conditions

The grid form utilized in all regions is quadrilateral since it is less complicated and requires less calculating time. Because mixing does not occur in this location, liquid nitrogen and nano lubricant streams were the least densely gridded. There is a 0.5 mm mesh size in this section. Mass transport and turbulence are both high in the mixing region. As a result, this region is more tightly meshed than others in order to obtain greater precision. This area has a mesh size of 0.05 mm. Because the fluid activity in this location is modest, it was meshed fairly densely. This area has a mesh size of 0.1 mm.

The input boundary was named "Pressure inlet" so the liquid nitrogen was supplied at a constant pressure from the outside. Outlets for mass flow and pressure were selected from the nano lubricant flow and the boundary wall, respectively. Domains such as the two streams, the mixing region, and the nozzle outlet were partitioned using the "inside" boundary condition. nMQL and liquid nitrogen maintain identical temperatures because no heat is transferred between them. Droplets are assumed to be perfectly spherical, and nanoparticles are injected place at a single times per second, resulting in a steady flow.

TABLE 1:DIMENSIONS OF THE CFD SPRAY NOZZLE

Serial No.	Parameters	value
1	Air orifice diameter	0.6 mm
2	Oil orifice diameter	0.7 mm
3	Ratio	1.16

B. CFD Simulation

The computational models for mist atomization were chosen after studying comparable sorts of simulations in sectors such as IC engines, medicinal applications, and fire extinguishers. There are three different multiphase models that can be used, including the Mixture model, the Volume of Fluid (VOF) model, and the Discrete Phase Model. In VOF models, the Eulerian approach is used to evaluate two-phase flow in fluids; however, since there is a presence of smaller droplets in the MQL process, this method has its own limits during simulation. More time and money will be required to simulate the breakup of droplets on the micrometer scale. Hence, a DPM was used to model atomization in a turbulent environment. In the DPM model, air is considered a continuum while particles of cutting fluid are considered discrete particles, in accordance with the Euler-Lagrange approach. The fundamental or continuous phase is calculated using the model's mass, momentum, and energy equations. Solving transportation and force balance equations yields DPM characteristics. Coalescence and particle disintegration were imposed by the CFD program's predefined sub-models. The discrete second phase was modelled using Lagrangian methods. The secondary discrete phase only accounts for a small percentage of the total volume. Table 2 shows the various models and scenarios used. A continuous phase interaction was used all through the simulation to eliminate approximations and bring the simulated observations closer to the experimental values, as the velocity difference between the two phases was larger than in the former case. This allows the discrete phase, oil droplets in this case, to interact with the surrounding air by exchanging velocity, mass, and energy. For 0.2 seconds, the spray was seen with unstable particle tracking enabled. There are four different drag laws available in FLUENT, including the Stokes-Cunningham, round, no spherical, and high-Mach-number laws.

TABLE 2: PARAMETERS USED IN ANSYS FLUENT

Model/Parameters	Value
Multiphase flow model	Discrete Phase Model
No of elements	1, 55, 486
Mesh type	Uniform
Solver	DP, second order, simple
Turbulence model	Realizable k - ε
Interaction with continuous phase	on
Unsteady particle tracking	on
Pressure (p)	2, 3, 4 bars
Droplet breakup	Wave type
Drag law	Spherical
Particle time step size (s)	0.000001
Flow rate	60, 80, 100 ml/h
Standoff	100mm
Diameter distribution	Rosin-Rammler

The spherical law works best with this model. Considering the particle to be spherical in this spherical drag rule is a reasonable approximation for the oil spray generation in MQL. Simulations of droplet fragmentation using the WAV breakdown model.

RESULT AND DISCUSSION

Theconditions that were used in the computational models, and the values that were entered for the parameters were all described in the reviewed literature. In order to obtain parameters for the boundary conditions, the simulation was carried out using all nine different scenarios. Iterations for the unstable state were carried out up until the point where the simulation for 0.2 seconds under each condition was created. Iterations continued until the mesh had a residual error of less than 0.0001, which was the set threshold. As a result of the DPM post-processing summary that was provided, the SMD droplet diameter was successfully reached. The most typical application for SMD is in simulations intended to replicate the behavior of aerosol sprays. The spray mean diameter (SMD) is measured in terms of the diameter of a spherical droplet that has the same surface area to volume ratio as the spray as a whole. In addition to that, the mean droplet velocity was measured and noted down for use in the future. In order to find out what the best size for the elements should be, grid independence tests were carried out. Under any and all conditions, it is presumed that the standoff distance will remain unchanged. A summary of the results of the post-processing for DPM was created for each and every simulation. The tests were carried out multiple times to guarantee their repeatability.

TABLE 3:DIAMETER AND VELOCITY FOR DIFFERENT CONDITIONS

PRESSURE (IN BARS)	FLOW RATE (ML/H)	SMD (μM)	VELOCITY OF DROPLET (M/S)
2	60	20	26
2	80	11.666	27
2	100	6.0578	32.18
3	60	19.1423	26.988
3	80	10.3615	33.89
3	100	6.057	32.78
4	60	16.05	26.84
4	80	7.2	32
4	100	3.5	39.63

Both simulated SMD and average velocity are displayed in Table 3. The droplets characteristics of a gas and liquid MQL jet are largely determined by the main phase, which is typically compressed LN2. Increasing pressure causes droplet size decrease, which is in turn caused by an increased flow rate. When the pressure or the mass flow rate increases, the velocity also increases.

The contours of larger, medium, and smaller droplet sizes, each with their own respective velocities, are shown in the following figures.

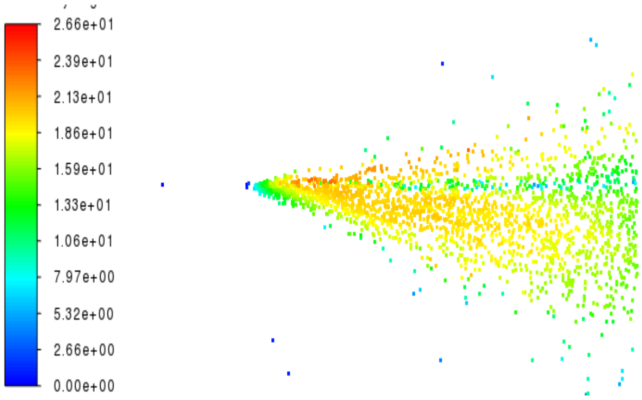

Figure 2: Minimum mean velocity 26 m/s.

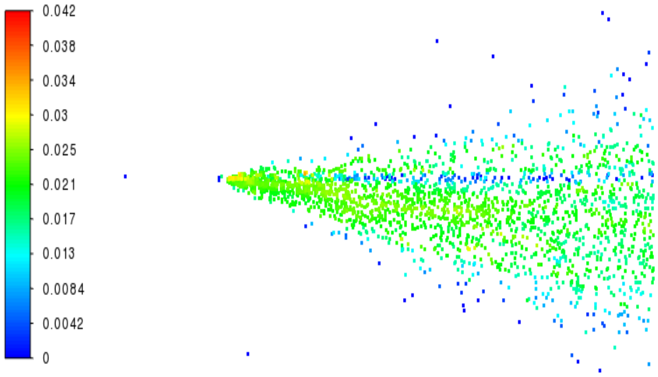

Figure. 3: Maximum dropletsize 26 μm.

In the scenario involving two bar pressure and 60 ml/h volumetric flow rate, the biggest droplet size (26 μm) and least mean velocity (26 m/s) were found in Figs. 2 and 3. Because of their greater bulk, larger droplets cannot be pumped to the cutting area to provide lubrication. surface roughness increases with droplet size, leading to an increase in the number of force components.

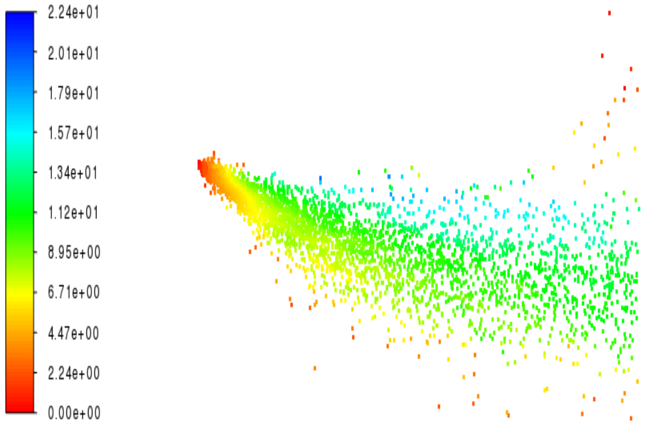

Figure 4:Mean velocity of medium droplets 26.84 m/s.

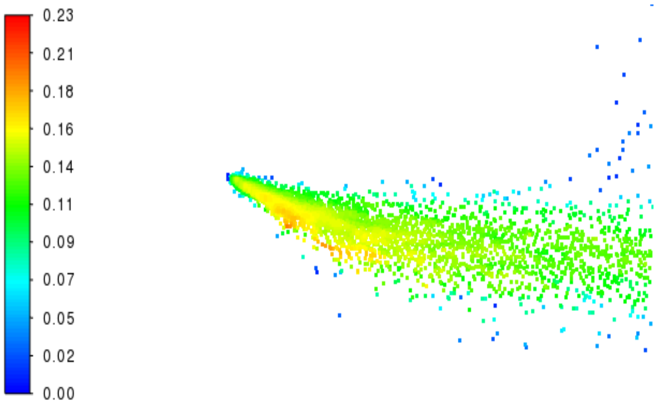

Figure 5:Medium droplet size 16.05 µm.

Here in Fig. 4 and Fig. 5the medium droplet size (16.05 µm) and respective mean velocity (26.84 m/s) while its 4-bar pressure and 60 ml/h mass flow rate of nano lubricant.Medium-sized droplets may readily enter the cutting zone and improve surface quality, providing an effective lubrication environment. Flushing the chips with pressurized LN_2 (flushing effect) aids in maintaining an excellent surface finish. Feed force decreases when lubricant droplet sizes around (16.05µm) due to improved lubrication at the tool-chip contact.

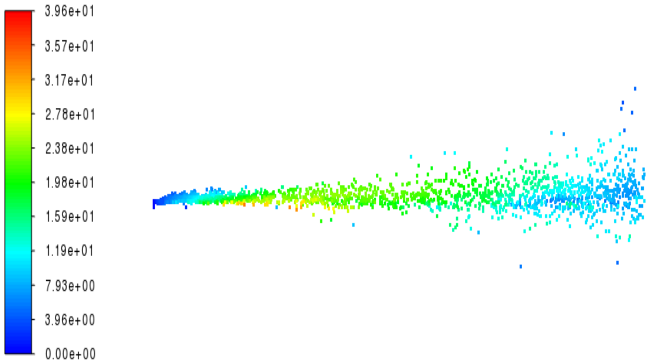

Figure 6:Maximum velocity 39.63 m/s.

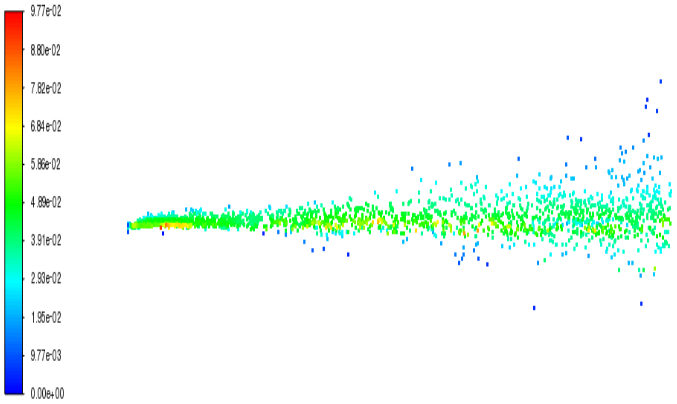

Figure 7: Minimum droplet size 3.5 µm.

Here, the smallest droplet size (3.5 µm) was discovered in the case of 4 bar pressure and 100 ml/h mass flow rate, as shown in Fig. 6 and Fig. 7.It is difficult for smaller droplets to travel in the open air. Due to its high cutting speed, the chip is readily dislodged, resulting in inadequate lubrication at the contact between the tool and the chip.

The effectiveness of a hybrid lubri-coolant depends on how easily the droplet can be accessed and how much of the tool-work contact zone can be wetted. Ineffective lubrication occurs because larger droplets with high inertia may fall early and be unable to travel in the working zone, while very tiny droplets, because of their tiny mass, are unable to proceed to the cutting zone and deviate from the flow route. Droplets can enter the working zone more effectively at higher pressures (4 bar), leading to a more thoroughly wetted (lubricated) tool-chip interface. Changes in pressure and mass flowrate cause a corresponding shift in lubricant droplet size. An increase in pressure causes the lubri-cooling mist to break up into even smaller droplets and accelerate away from the chip-tool contact. If the mist can get deep enough into the workpiece, the cutting forces could be reduced. When the pressure is raised, the droplets of lubricating mist are able to remove more heat from the interface between the machine tool and the workpiece, thereby reducing the likelihood of chips adhering to the tool surface and the development of built-up edges. So, in order to generate an appropriate droplet distribution, this simulation finds a range of droplet sizes, the middle of which is a medium-sized droplet.

CONCLUSIONS

In order to evaluate the significance of spray parameters including droplet size and velocity, the current work employs a hybrid lubri-coolant environment. To further understand the effects of droplet size and velocity during machining, a numerical analysis is used as a powerful tool.

The following are the key findings of the current investigation:

1. The coolant's efficiency is determined by the CFD analysis where the droplet size distribution and velocity play a greater role.
2. The computer modeling clearly demonstrates that the droplet size shrinks with both the flow rate and the atomization pressure.
3. A medium-sized (16.05µm) droplet with a greater pressure (4 bars) can provide adequate lubrication due to their size and velocity, and according to literature review during machining these type droplets can minimize cutting forces, and improve surface smoothness.

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