

Article

Thermophysical Properties and Heat Transfer Performance of Novel Dry-Ice-Based Sustainable Hybrid Lubri-Coolant

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Abstract: It is a well-known fact that the consumption of conventional cutting fluids in metalworking industries leads to severe health and environmental issues. Owing to the EPA (Environmental Protection Agency) increasing regulations regarding pollution and contamination, there is a dire need for a greener fluid with excellent cooling and lubrication characteristics to diminish the environmental impact of cutting fluids, as well as to improve machinability. Cryogenics are greener and excellent coolants but poor lubricants, while ester oils are excellent lubricants and poor coolants. Therefore, a hybrid lubri-coolant cutting fluid with synergistic cooling and lubrication characteristics could be a desideratum to replace conventional cutting fluid. To investigate a newly proposed hybrid lubri-coolant, thermophysical properties (density, thermal conductivity, specific heat, and viscosity), heat transfer properties (surface temperature, heat flux, and heat transfer coefficient), and machinability properties (tool life, etc.) are key characteristics of the fluids that decide phase change and heat dissipation capabilities during their application in machining. In the current experimental study, hybrid ethanol–ester oils with/without dry ice (−78 °C) are proposed as cutting fluids and holistically investigated in terms of thermo-physical properties, heat transfer properties, and machinability properties under different cutting conditions. Experimental findings have depicted a 20%, 10%, and 5% decrease in density, specific heat, and viscosity, respectively, with a 15% increase in the thermal conductivity of the fluid with the addition of dry ice. The dry-ice-based hybrid lubri-coolant sprayed onto a Ti-6Al-4V plate enhanced the heat transfer coefficient significantly by 17% compared to hybrid lubri-coolant without dry ice. Besides, hybrid ethanol–ester oil dry ice was treated as a trendsetter and indicated an 11% improvement of the tool life at a cutting speed of 75 m/min and a feed rate of 0.04 mm/z. Therefore, dry-ice-based hybrid lubri-coolant can be applied as a cutting fluid by practitioners in aerospace, automotive, prosthetic body parts manufacturing, and manufacturing industries.

Keywords: thermophysical properties; heat transfer coefficient; cutting fluid; ethanol; ester oil



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1. Introduction

Dry machining is one of the sustainable machining alternatives with less environmental impact; however, no lubrication allows for an elevated cutting temperature, leading to accelerated tool wear, especially in the machining of difficult-to-cut materials. The mineral-based conventional cutting fluids play a key role in improving the surface quality, tool wear, and overall machinability of metals and alloys [1,2]. An immense quantity of cutting fluid is generally applied in industry to achieve sufficient cooling and lubrication. However, the immoderate quantity of mineral-based cutting fluids comes with numerous health and environmental complexities [3]. It is reported in the literature that global consumption of mineral-based fluids in 2016 was 13,726 million tons, with a 1% annual increment. The

global community is also reinforcing sustainable manufacturing under strict regulations imposed by the EPA to build a bridge between technology and the environment. Besides, the danger of natural lubricants and natural energy resources is that the loss proportion varies between 13 and ~50% in terrestrial and aquatic ecosystems. The cooling cost contributes to 10~17% of the total machining cost [4]. Therefore, there is a dire need to bring forth economical and green cutting fluids as an alternative to conventional mineral-based fluids.

Recently, sustainability trends have emerged incorporating social, economic, and ecological perspectives [5]. To apply sustainable production, the latest research is opening an avenue for an efficient lubri-coolant as a perfect alternative to conventional cooling. The effectiveness of cutting fluid is associated with possessing sufficient lubrication and heat transfer capabilities. Thermophysical properties [6] such as density, thermal conductivity [7], specific heat [8], and viscosity are the key coolant/lubricant characteristics that decide the phase change, lubrication, and heat transfer properties of the cutting fluids. The lubrication characteristic of cutting fluid is highly associated with viscosity and density, while cooling capabilities mainly depend upon thermal conductivity and specific heat. Heat transfer is the most important characteristic of the fluid due to the shorter stay time of cutting fluid, specifically in high-speed machining. Most cutting fluids dissipate heat mainly by conduction, convection, and evaporation, while cryogenic coolants dissipate heat by evaporation and sublimation. The evaporation or sublimation mainly depends upon the viscosity of the specific fluid. Sublimation has the capability to dissipate heat more quickly than evaporation or conduction.

Cryogenic coolants (LN_2 , dry ice) have extremely low boiling temperatures, so applying cryogenic coolants rapidly dissipates the cutting temperature. Wang et al. [9] determined the heat transfer rate of LN_2 by spraying it onto a static plate. Experimental results indicated that the extremely low temperature of LN_2 burst the evaporation film and improved the heat transfer of the plate. Bermingham et al. [10] have applied cryogenic LN_2 in the machining of Ti-6Al-4V at different feed rates and depths of cut. The authors' findings have depicted prolonged tool life with the advantage of heat extraction from the cutting zone. However, it was proposed that cryogenic cooling may not extract frictional heat from the cutting zone. Pusavec et al. [11] investigated the cooling capabilities of cryogenic LN_2 and CO_2 in the milling of Ti-6Al-4V. The heat transfer rates of cryogenic LN_2 and CO_2 were analyzed for two cryogenic modes and compared to emulsion cooling. The authors' findings depicted that cutting temperature under CO_2 was lower than under LN_2 due to the high heat transfer rate. Jebaraj et al. [12] have carried out the milling of NiCrMo steel under the effects of LN_2 and CO_2 coolants and compared them to conventional flood cooling. The use of LN_2 and CO_2 caused reductions of 53% and 50% more in cutting temperature than wet cooling, respectively. However, a significant reduction in surface roughness was observed under CO_2 compared to LN_2 . Jamil et al. [13] put forward a comparison of the heat transfer of cryogenic- LN_2 and CO_2 on a static plate of Ti-6Al-4V and determined the cutting temperature under machining. The authors reported extremely low temperature under cryogenic- LN_2 compared to CO_2 ; however, the heat transfer rate under compressed CO_2 was higher than under cryogenic- LN_2 . The high latent heat of the sublimation (573 kJ/kg at -78°C) of dry ice dissipated the heat efficiency more than the latent heat of the vaporization of LN_2 (411 kJ/kg), resulting in a high rate of heat transfer. Besides, dry ice rapidly sublimates to gaseous CO_2 and reduces the temperature to -78°C without leaving any residue. The relatively better performance of compressed CO_2 than LN_2 can be associated with a longer stay of CO_2 on the cutting zone and its collection of the surrounding moistures on the cutting zone, making it wet and lubricative in nature. However, this lubrication is not enough for machining. Therefore, the provision of superior and synergistic cooling and lubrication could be an alternative to conventional cooling.

Recently, there is research going on involving exploring sustainable hybrid lubri-cooling that provides cooling and lubrication [14]. The hybrid lubri-coolant combines a cryogen as a coolant and oil as a lubricant to achieve appropriate cooling and lubrication [15]. Centidag et al. [16] carried out experiments by machining hard-to-cut material in

terms of tool wear and surface integrity under CO₂, minimum quantity lubrication (MQL), and hybrid cryoMQL mist. The findings depicted superior machinability achieved under hybrid cryoMQL due to cooling as well as lubrication. Krishnamurthy et al. [17] have compared ethanol, cryogenic-LN₂, conventional flood cooling, and hybrid cryo-ethanol in the machining of Ti alloy. The use of ethanol-blended metalworking fluid reduced the cutting forces, chip adhesion on the tool cutting edge, and surface roughness. This can be associated with the -OH group of ethanol passivating the carbon surface of the cutting tool and preventing chip adhesion on the main cutting edge of the cutting tool. Liu et al. [18] investigated heat transfer under spray cooling of ethanol–water mixtures. It was observed that heat transfer under ethanol–water mixture was higher than under pure water. It was associated with the low surface tension of ethanol–water due to the presence of ethanol that helped to break mixture droplets into fine droplets and increased the heat transfer. Additionally, ethanol reduced the overall boiling point of the mixture, initiated two-phase behavior, and enhanced the nucleation boiling heat transfer [19]. The lower density and specific heat helped to increase the heat transfer performance. Ethanol also has the capability to rapidly mix with the cryogen without freezing to solid ethanol.

The shortcomings of previous research studies and the scientific contribution of the proposed study can be summarized in terms of the following key points: (1) Dry machining is one of the sustainable alternatives, but high cutting temperature rapidly reduces the tool wear. (2) Flood cooling is good enough to control the heat, but it damages our environment significantly. (3) Cryogenic has superior cooling but poor lubrication, while MQL is vice versa; therefore, hybrid cryoMQL is reported as an effective way to improve machinability. (4) The addition of ethanol to the cutting fluid reduces the adhesion of the chip, dissolves most of the particles, has no contamination effect, behaves as coolant, and rapidly dissolves the dry ice to gaseous CO₂. It can be concluded from the above literature that hybrid cooling-lubricant with ethanol mixed in could be the alternative to conventional cooling and can play a key role in improving the machinability of cutting materials.

In this current study, a newly developed ethanol (behaves as coolant)–ester oil (behaves as a lubricant) mixture is proposed as lubri-coolant for machining with and without the addition of dry ice. To propose a hybrid lubri-coolant, ethanol–ester oil in the ratios of 1:0.25, 1:0.5, and 1:1 is mixed with the addition of dry ice equal in weight to the fluid mixture. The thermophysical properties (density, specific heat, thermal conductivity, and viscosity) under different temperatures with and without dry ice are investigated. The addition of dry ice (coolant at −78 °C) can change the thermophysical properties and heat transfer capabilities due to the extremely low temperature of dry ice. Moreover, a static thin plate is sprayed to calculate the surface heat dissipation and heat transfer coefficient under hybrid lubri-coolant spray cooling. The heat transfer properties (surface temperature, heat flux, heat transfer coefficient) are also investigated. Therefore, a missing correlation between thermophysical properties (density, thermal conductivity, specific heat, viscosity) and temperature can be determined with and without the addition of dry ice.

2. Materials and Methods

This section presents the thermophysical properties of coolant and lubricant, sample preparation, and measurement equipment to quantify the thermophysical properties.

2.1. Thermophysical Characteristic of Hybrid Coolant/Lubricant

In this study, hybrid ethanol–ester oil–dry ice lubri-coolant is proposed as a cutting medium. In this hybrid lubri-coolant, ethanol (procured from Nanjing Chemical Reagent Co., Ltd., Nanjing, China) behaves as a coolant, while ester oil (Vascomill MMS FA-1, Blaser SwissLube, Hasle Ruegsau, Switzerland) behaves as a lubricant. Table 1 depicts the thermophysical properties of ethanol, ester oil, and dry ice.

Table 1. Thermophysical properties of ethanol, ester oil, and dry ice at room temperature.

Material	Melting Point, MP (°C)	Boiling Point, BP (°C)	Density, ρ (g/mL)	Thermal Conductivity, k (W/mK)	Specific Heat, Cp (kJ/kgK)	Viscosity, μ (mPa.s)
Ethanol	−114.1	78.5	0.789~0.791 at 20 °C	0.17 at 20 °C	2.44	1.275
Ester oil	-	-	0.85 at 20 °C	0.16	1.68	44.26
Dry ice	-	−78.464	1511 kg/m ³ at −78 °C	0.01663	0.849	

2.2. Sample Preparation of Hybrid Coolant/Lubricant

To determine the thermophysical properties (density, thermal conductivity, specific heat, and viscosity) of samples of ethanol–ester oil without dry ice, the ethanol–ester oil was mixed in the ratios of 1:0.25, 1:0.50, and 1:1 as provided in Table 2. For the samples with dry ice, ethanol–ester oil was mixed in the ratios of 1:0.25, 1:0.50, and 1:1, and dry ice was mixed in at an equal weight to the ethanol–ester oil mixture, as the addition of an equal amount of dry ice in ethanol mixture can keep the mixture temperature at −78 °C for a long time (for instance, 26 min for liquid of 60 mL and addition of 60 g of dry ice). Besides, a wide range of temperatures is covered without dry ice (10~30 °C), and with dry ice, the −75~0 °C temperature range is covered.

Table 2. Samples preparation to test thermophysical testing.

Samples	Sr #	No Dry Ice	Sr #	Dry Ice
Pure ethanol	1	Ethanol = 60 mL	6	Ethanol = 60 mL Dry ice = 60 g
Pure ester oil	2	Ester oil = 60 mL	7	Ester oil = 60 mL Dry ice = 60 g
Hybrid ethanol–ester oil (1:0.25)	3	Ethanol = 48 mL Ester oil = 12 mL	8	Ethanol = 48 mL Ester oil = 12 mL Dry ice = 60 g
Hybrid ethanol–ester oil (1:0.5)	4	Ethanol = 40 mL Ester oil = 20 mL	9	Ethanol = 40 mL Ester oil = 20 mL Dry ice = 60 g
Hybrid ethanol–ester oil (1:1)	5	Ethanol = 30 mL Ester oil = 30 mL	10	Ethanol = 30 mL Ester oil = 30 mL Dry ice = 60 g

Figure 1 highlights the sample preparation mechanism to form hybrid lubri-coolant. Initially, ethanol–ester oil is mixed in (1:0.25), (1:0.5), and (1:1) weight ratios and ultrasonicated for 10 min. For the dry ice samples, ethanol–ester oil is mixed and ultrasonicated, and dry ice is added. Additionally, this hybrid lubri-coolant is eco-benign and has a synergistic effect of cooling and lubrication.

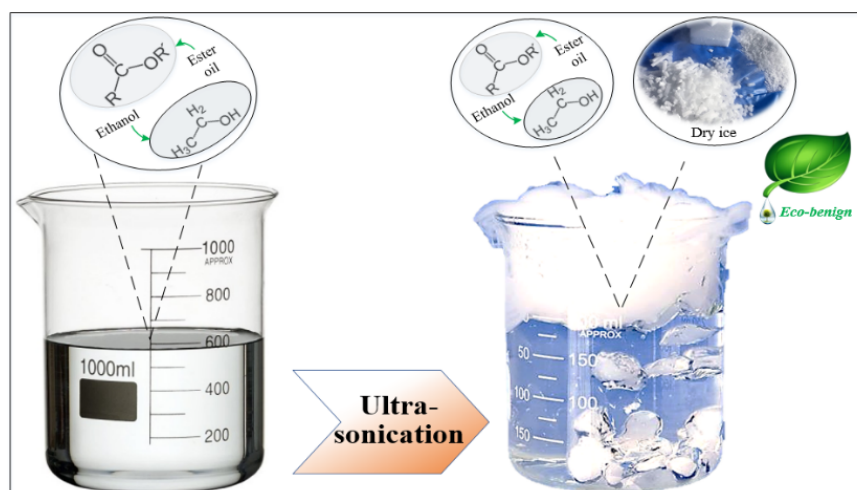


Figure 1. Preparation procedure of hybrid lubri-coolant.

2.3. Thermophysical Measurement Equipment

Density: For two-phase (gas–liquid) fluids, the mixture density is difficult to achieve in terms of empirical models. However, numerous numeric models are available in the open literature to solve two-phase (liquid–solid) fluid density [20]. The well-known formula which is used for liquid–solid/liquid–liquid two-phase fluids at 20 °C is as follows:

$$\rho_{mix} = \rho_{ethanol}(1 - \varphi_{oil}) + \varphi_{oil}\rho_{oil} \text{ at } 20^\circ\text{C temperature} \quad (1)$$

where ρ_{mix} is the density of hybrid ethanol–ester oil, $\rho_{ethanol}$ is the density of ethanol, φ_{oil} is the volume percentage of oil, and ρ_{oil} is the density of ester oil. The volume percentage of oil φ_{oil} can be determined using the following relation Equation (2):

$$\text{Vol.\% of oil } \varphi_{oil} = \frac{m_{oil}/\rho_{oil}}{m_{oil}/\rho_{oil} + m_{ethanol}/\rho_{ethanol}} \text{ at } 20^\circ\text{C temperature} \quad (2)$$

where m_{oil} is the mass of ester oil and $m_{ethanol}$ is the mass of ethanol in grams. Therefore, a general relation for converting liters to grams could be determined by multiplying the ethanol quantity of 'x' (liters) by 1000 cm³ and the density of ethanol. Similarly, converting liters to grams of ester oil 'y' (liters) can be determined by multiplying 1000 cm³ and the density of ester oil.

$$\text{Ethanol(gram)} = x \text{ (Liter)} \times \frac{10^3\text{cm}^3}{1(\text{L})} \times \text{density of ethanol} \left(\frac{\text{g}}{\text{cm}^3} \right) \quad (3)$$

$$\text{Ester oil(gram)} = y \text{ (Liter)} \times \frac{10^3\text{cm}^3}{1(\text{L})} \times \text{density of ester oil} \frac{\text{g}}{\text{cm}^3} \quad (4)$$

Figure 2 shows the digital precision scale (DPTOP) with a precision of ± 0.001 to determine the masses of the fluids. By taking the ratio of mass and volume of the fluid, the density of the fluid was determined.



Figure 2. The digital precision scale to determine density.

Thermal conductivity: It is one of the most important parameters to express the heat transfer efficiency of a liquid. The Maxwell relation is normally used to predict the thermal conductivity of the mixture as a function of concentration variation. To find the thermal conductivity of the binary mixture's fluids, Jamieson's [21] correlation was applied. This correlation is based on already found thermal conductivities of individual fluids:

$$\lambda_m = w_1\lambda_1 + w_2\lambda_2 - \alpha(\lambda_2 - \lambda_1) \left[1 - (w_2)^{1/2} \right] w_2 \quad (5)$$

where $w_1 = \frac{\text{mass of solute 1}}{\text{Total mass of solution}}$ and $w_2 = \frac{\text{mass of solute 2}}{\text{Total mass of solution}}$ are the weight fractions for the binary liquids, respectively, provided that $\lambda_2 \geq \lambda_1$. α is the adjustable parameter, and it can be set as '1' if the mixture's thermal conductivity data are unavailable for regression. The generated heat enters the material through the sensor, during which a voltage drop occurs rapidly at the heating source. The thermal conductivity is calculated through the voltage drop data. This highly reliable technique is based on the transient plane source (TPS) method. A spiral-type heating source is located at the center of the sensor, where heat is generated. The thermal conductivities of ethanol, ester oil, and hybrid ethanol–ester oil (1:0.25), (1:0.5), and (1:1) are determined by the C-Therm thermal conductivity analyzer. The TCi consists of a sensor, a power control device, and computer software, shown in Figure 3. C-Therm has the capacity to measure in the range of 0–500 W/mK and at temperatures in the range of -100 °C to 200 °C for the standard sensor. It is easy to use with non-destructive samples for liquids, fluids, powders, and pastes. For the measurement, the ASTM-D7984 standard was followed. The precision of C-Therm TCi™ (Thermal Conductivity Analyzer: TH89-05-0025) changes from 0.5 to 1%. The measurement time of the C-Therm sample is 1 to 3 s.

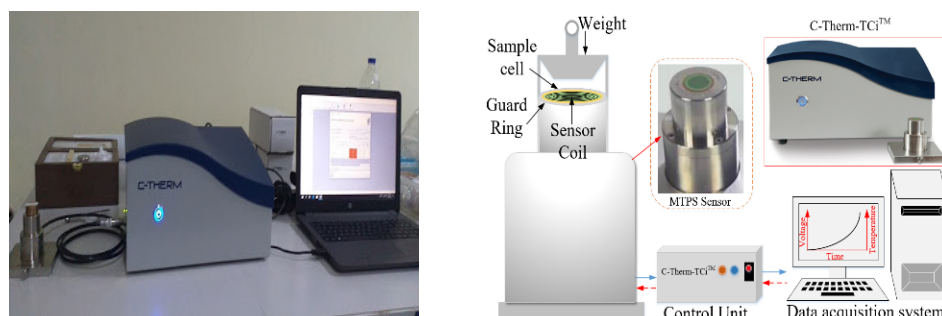


Figure 3. Liquid thermal conductivity measurement mechanism.

Specific heat: It is also among the fundamental thermal properties of any liquid/coolant to evaluate its heat carrying capacity. The specific heat capacity was measured by differential scanning calorimetry (Model: NETZSCH-DSC-200 F3) at the temperature rate of 15 K/min. Differential scanning calorimetry (ISO-11357) is a technique that detects the variation in heat flow and temperature by the heat capacity of fluid or by the endothermic/exothermic process of fluid over time and the rate of temperature change as a function. NETZSCH-DSC-200 F3 operates in the range of $-105\text{ }^{\circ}\text{C}$ to $600\text{ }^{\circ}\text{C}$ because it is equipped with liquid nitrogen (20 mL/min). The sample fluid is enclosed in an aluminum crucible at a sample volume of 20 mL. Figure 4 shows the differential scanning calorimeter for specific heat measurements. For the mixture of ethanol–ester oil, the oil and ethanol are ultrasonicated for 6.5 min. The specific heat was recorded with the change in temperature calculated as follows:

$$Cp_{mix} = \frac{m_{LN2}Cp_{LN2}(\theta_2 - \theta)}{m_{mix}(\theta - \theta_1)} \quad (6)$$

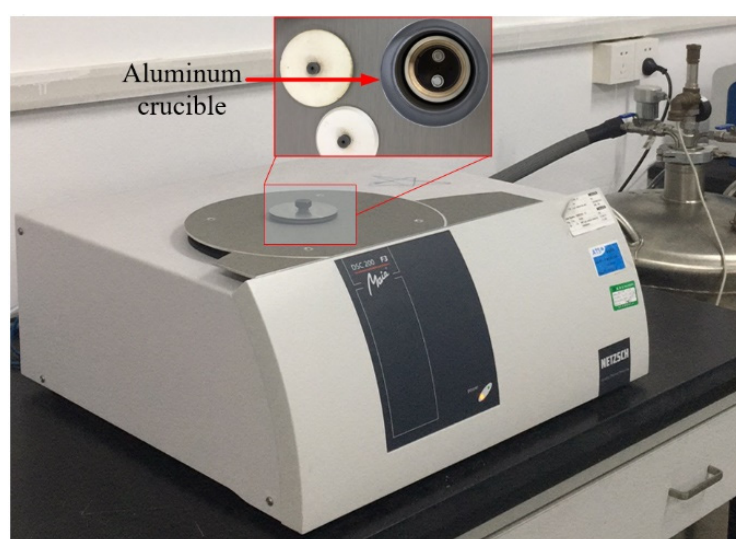


Figure 4. NETZSCH-DSC-200 F3 Differential Scanning Calorimeter (DSC).

Here Cp_{mix} is the specific heat of hybrid lubri-coolant ($\text{J/g } ^{\circ}\text{C}$), m_{LN2} is the mass of liquid nitrogen, Cp_{LN2} is the specific heat of liquid nitrogen, and $(LN2\text{ temperature } \theta_2 - \text{fluid varied temperature } \theta)$ is the difference between the temperature of LN_2 and fluid temperature. Besides, m_{mix} is the mass of the fluid and $(\text{fluid varied temperature } \theta - \text{fluid initial temperature } \theta_1)$ is the change in temperature of the fluid.

Viscosity: In these experiments, the viscosity of ethanol, oil, and ethanol–ester oil (1:0.25), (1:0.5), and (1:1) were determined using the Thermo Scientific HAAKE MARS 60 Rheometer. The shear rate of $100/\text{s}$ was kept constant. The temperature range was $-150\text{ }^{\circ}\text{C}$ to $600\text{ }^{\circ}\text{C}$. The heating rate of $5\text{ }^{\circ}\text{C}/\text{min}$ was used throughout the measurements (Figure 5). This viscometer contains a dynamic chamber where the fluid is stored to test. To determine the viscosity of a Newtonian fluid, the following relation is used:

$$\tau = u\gamma \quad (7)$$



Figure 5. HAAKE MARS 60 Viscometer.

Here, τ is the shear stress (Pa), u is the viscosity (mPa.s), and γ is the shear strain rate (1/s).

3. Results and Discussion

This section provides a concise description of the experimental results and the experimental conclusions that can be drawn.

3.1. Density

Figure 6 shows the variation in densities of ethanol, ester oil (fatty alcohol), and ethanol–ester oil (1:0.25), (1:0.5), and (1:1) at five different temperatures. The density of all the fluids decreased with the increase of temperature. As the temperature increases, the liquid and gas molecules move rapidly and collide with each other. These collisions cause the molecules to become far results in increase in volume. Therefore, few molecules within the specific volume decrease the densities of the liquids and gases [22]. Similarly, a temperature decrease moves the molecules slowly, resulting in less collision and space between the molecules. The ester oil (fatty alcohol) had the highest density of 0.857 g/mL at 10 °C and decreased to 0.84 g/mL at 35 °C. Similarly, ethanol had a minimum density among all the hybrid lubri-coolants. Its density varied from 0.80 g/mL at 10 °C and 0.774 °C at 30. Besides, the density of ethanol–ester oil (1:0.25) remained slightly higher than that of pure ethanol at all temperatures. The density of ethanol–ester oil (1:1) was higher than those of (1:0.5) and (1:0.25). It could be associated with the increase in oil concentration in the mixture of ethanol–ester oil. The addition of dry ice suddenly lowers the temperature, but it makes voids in the fluid, resulting in a sudden decrease in density. The rapid decrease in density was most significant in ethanol because ethanol quickly dissolves dry ice. After the evaporation of dry ice, the temperature increased from −76 °C to room temperature. As dry ice evaporates, the voids in the coolant also decrease, increasing density. Therefore, the density of ethanol was lower than those of the ester oil and ethanol–ester oil hybrid lubri-coolants. However, this trend was the opposite in the case of ester oil. The addition of dry ice increased the density of ester oil, as the ester oil did not dissolve the dry ice quickly. Only a small quantity of dry ice evaporated by making agglomeration in the oil by decreasing the volume. Therefore, due to a decrease in volume, the density of ester oil was increased at low temperatures, and its density was decreased as the temperature of the coolant approached room temperature.

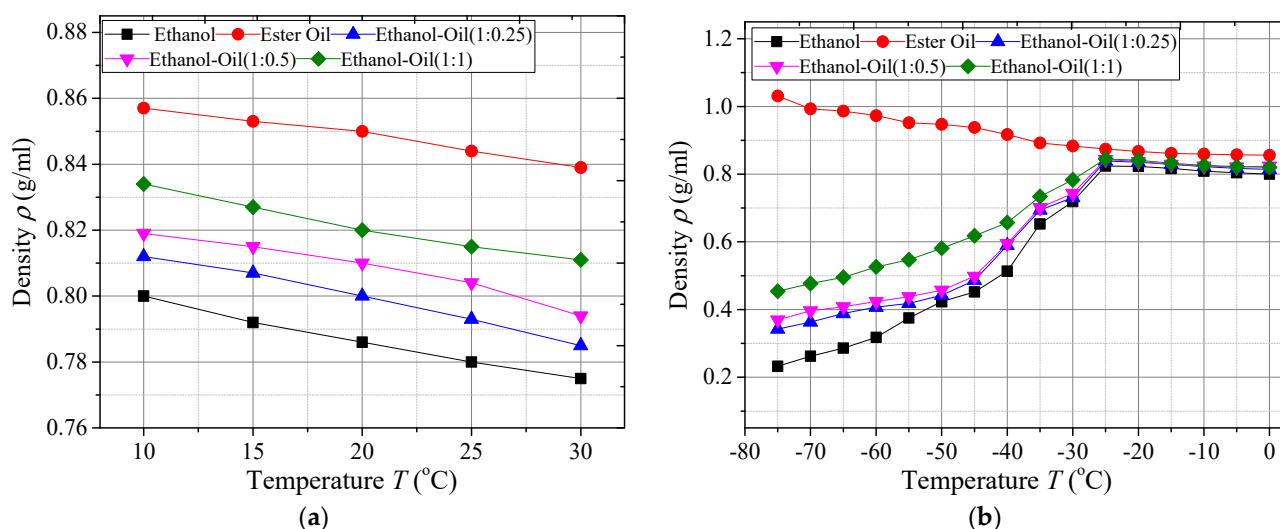


Figure 6. The density of coolants/lubricants under variation in temperature. (a) No dry ice; (b) dry ice.

At room temperature (10 °C), ethanol had a density of 0.80 g/mL, ester oil a density of 0.857 g/mL, hybrid ethanol–ester oil (1:0.25) a density of 0.814 g/mL, hybrid ethanol–ester oil (1:0.5) a density of 0.819 g/mL, and hybrid ethanol–ester oil (1:1) a density of 0.834 g/mL; the density of all the coolants/lubricants decreased with the increase in cutting temperature. Similarly, with the addition of dry ice (−76 °C), a rapid decrease in density occurred due to the formation of two-phase fluids. At −76 °C, the density of ethanol was 0.23 g/mL, the density of ester oil was 1.033 g/mL, that of hybrid ethanol–ester oil (1:0.25) was 0.34 g/mL, that of hybrid ethanol–ester oil (1:0.5) was 0.36 g/mL, and that of hybrid ethanol–ester oil (1:1) was 0.45 g/mL. The addition of dry ice made dynamic two-phase fluids of ethanol and hybrid ethanol–ester oil (1:0.25), (1:0.5), and (1:1), and rapidly decreased their density. A comparison of densities with/without dry ice depicted a decrease of 71%, 60.65%, 56%, and 46% with dry ice for ethanol, hybrid ethanol–ester oil (1:0.25), hybrid ethanol–ester oil (1:0.5), and hybrid ethanol–ester oil (1:1), respectively. On the contrary, the density of ester oil increased by 20.33% with the addition of dry ice. An increase in the density of ester oil could be associated with the formation of agglomeration that is unable to make dry ice a two-phase fluid.

3.2. Thermal Conductivity

Figure 7 shows the thermal conductivity versus temperature plot in the range of 10–30 °C for five hybrid lubri-coolants. At 10 °C, thermal conductivity measured by C-Therm was about 0.171, 0.169, 0.167, 0.164, 0.161 W/mK, for ethanol, ethanol–ester oil (1:0.25), ethanol–ester oil (1:0.5), ethanol–ester oil (1:1), and ester oil, respectively. The thermal conductivity of ethanol (0.171 W/mK) was found to be the highest among all the fluids at 10 °C [23], while ester oil had the lowest thermal conductivity of 0.161 W/mK at 30 °C. Although an increase in temperature decreased the thermal conductivity, temperature change has the least significant effect on the thermal conductivity of the hybrid lubri-coolants. At 30 °C, the thermal conductivity of ethanol was 0.168 W/mK, that of ethanol–ester oil (1:0.25) was 0.167 W/mK, that of ethanol–ester oil (1:0.5) was 0.165 W/mK, that of ethanol–ester oil (1:1) was 0.162 W/mK, and that of ester oil was 0.158 W/mK [24]. A small reduction in thermal conductivity was observed in this range of temperatures.

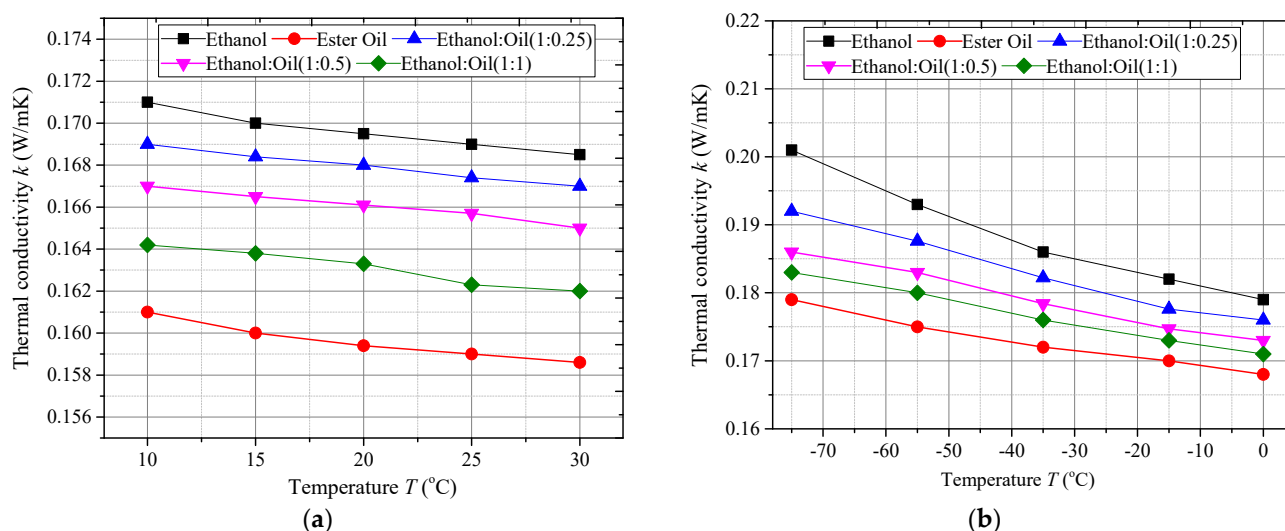


Figure 7. Thermal conductivity of coolants/lubricants under variation in temperature. (a) No dry ice; (b) dry ice.

The thermal conductivities of ethanol, ester oil, ethanol–ester oil (1:0.25), ethanol–ester oil (1:0.50), and ethanol–ester oil (1:1) with dry ice were determined under varying temperatures, as the addition of dry ice makes the liquid coolant reach -76 °C and evaporates directly from solid dry ice to gaseous CO_2 in the environment. Thermal conductivity decreased as the temperature increased from -75 °C to 0 °C. At -75 °C, the thermal conductivity of ethanol was 0.201 W/mK, and it decreased to 0.179 W/mK at 0 °C. Similarly, ethanol–ester oil (1:0.25) illustrated the maximum thermal conductivity of 0.192 W/mK to 0.176 W/mK as the temperature changed from -75 °C to 0 °C. Similarly, the thermal conductivity of ethanol–ester oil (1:0.5) decreased from 0.186 W/mK to 0.173 W/mK as the temperature approached 0 °C. The minimum thermal conductivity of ester oil was 0.179 W/mK at -75 °C, and it decreased to 0.167 W/mK at 0 °C. It is pertinent to mention that the thermal conductivity of ester oil did not change significantly under varying temperatures. The addition of dry ice increased the thermal conductivity, with an increase of 17.5% in ethanol, 11.2% in ester oil, 13.6% in hybrid ethanol–ester oil (1:0.25), 11.4% in hybrid ethanol–ester oil (1:0.5), and 11.6% in hybrid ethanol–ester oil (1:1).

3.3. Specific Heat

The specific heats of ethanol, ester oil, and ethanol–ester oil (1:0.25), (1:0.5), and (1:1) were determined with the variation in temperature in the range of 5 °C to 35 °C. The highest specific heat was achieved for ethanol from 2.35 J/g °C to 2.72 J/g °C when the temperature varied from 5 °C to 35 °C, while the minimum specific heat of ester oil varied from 1.57 J/g °C to 1.75 J/g °C as the temperature reached a maximum of 35 °C. Besides, ethanol–ester oil (1:0.25) has a higher specific heat (2.2 J/g °C– 2.53 J/g °C) than ethanol–ester oil (1:0.5), which has a specific heat of 2.06 J/g °C to 2.4 J/g °C (Figure 8). The increasing specific heat of ethanol–ester oil (1:0.25) could be associated with a high concentration of ethanol in the solution that increased the specific heat of the hybrid lubri-coolant.

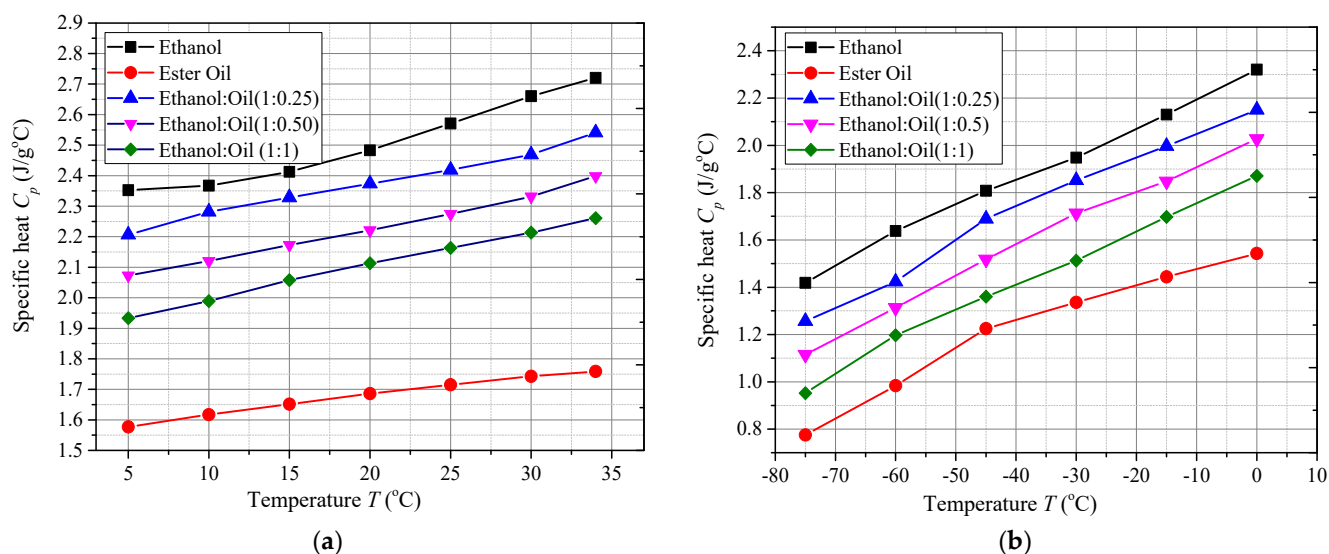


Figure 8. The specific heat of coolants/lubricants under variation in temperature. (a) No dry ice; (b) dry ice.

The specific heats of ethanol, ester oil, and ethanol–ester oil (1:0.25), (1:0.5), and (1:1) are determined with the addition of dry ice. It converts the single-phase fluids into two-phase fluids at low temperatures ($-75\text{ }^{\circ}\text{C}$). Later, dry ice evaporates, leaving the fluid in the crucible. The temperature increases, leading to an increase in specific heat. As can be seen from Figure 8, the increase in temperature increases the specific heat of the fluid. Besides, ethanol has the highest specific heat among all the fluids, while ester oil has the minimum within the range of $-75\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$. The specific heat of ethanol was $1.41\text{ J/g }^{\circ}\text{C}$ at $-75\text{ }^{\circ}\text{C}$, and it raised to $2.26\text{ J/g }^{\circ}\text{C}$ at $0\text{ }^{\circ}\text{C}$. Similarly, the specific heat of hybrid lubri-coolant ethanol–ester oil (1:0.25) was higher than those of ethanol–ester oil (1:0.5) and (1:1). The specific heat of ethanol–ester oil (1:0.25) being higher than that of ethanol–ester oil (1:0.5) or (1:1) could be associated with a higher quantity of ethanol that contributed to an increase in the specific heat.

A comparison of with/without dry ice depicted a 40% decrease in the specific heat of ethanol. The ester oil with dry ice showed a 50.4% reduction in specific heat, ethanol–ester oil (1:0.25) showed a 42.3% reduction in specific heat, ethanol–ester oil (1:0.5) shows 45.6%, and ethanol–ester oil (1:1) illustrates a 50.8% reduction in specific heat. In a nutshell, the addition of dry ice lowered the specific heat of the hybrid lubri-coolants.

3.4. Viscosity

Figure 9 shows the plot of varying viscosity under temperature change. It shows that the viscosity of the fluids decreases with the increase in temperature. A significant change in viscosity was observed for the ester oil, measuring $90\text{ mPa}\cdot\text{s}$ at $5\text{ }^{\circ}\text{C}$ and $28\text{ mPa}\cdot\text{s}$ at $35\text{ }^{\circ}\text{C}$. Besides, very little change in viscosity was observed in ethanol, ranging from $1.8\text{ mPa}\cdot\text{s}$ to $1\text{ mPa}\cdot\text{s}$ of viscosity. Besides, ethanol–ester oil (1:0.25) and (1:0.5) showed little change in viscosity with temperature change. It is pertinent to mention that ethanol–ester oil (1:1) also illustrated a significant change in viscosity with the temperature change. It could be associated with the concentration of ester oil that depicts the variation of viscosity with the temperature change. Figure 9 shows the viscosity of ethanol, ester oil, and ethanol–ester oil (1:0.25), (1:0.5), and (1:1) with the addition of dry ice. The addition of dry ice made the hybrid lubri-coolants two-phase fluids. A significant change in viscosity could be observed in the case of ester oil. It can be seen that $4.5\text{ mPa}\cdot\text{s}$ of viscosity was observed at $-76\text{ }^{\circ}\text{C}$, while it was $2.2\text{ mPa}\cdot\text{s}$ at $0\text{ }^{\circ}\text{C}$. A comparison of viscosity with and without dry ice shows a significant reduction in the viscosity of ester oil under dry ice. Under dry ice ($-75\text{ }^{\circ}\text{C}$), the percentage reduction in the viscosity of ester oil was 95%, the reduction in ethanol was 77.8%, the reduction in hybrid ethanol–ester oil (1:0.25) was 83.8%, the reduction in hybrid

ethanol–ester oil (1:0.5) was 79.8%, and the reduction in hybrid ethanol–ester oil (1:1) was 81.7%. This reduction can be associated with the coolant/lubricants and the addition of dry ice converting them to liquid and gas two-phase fluids.

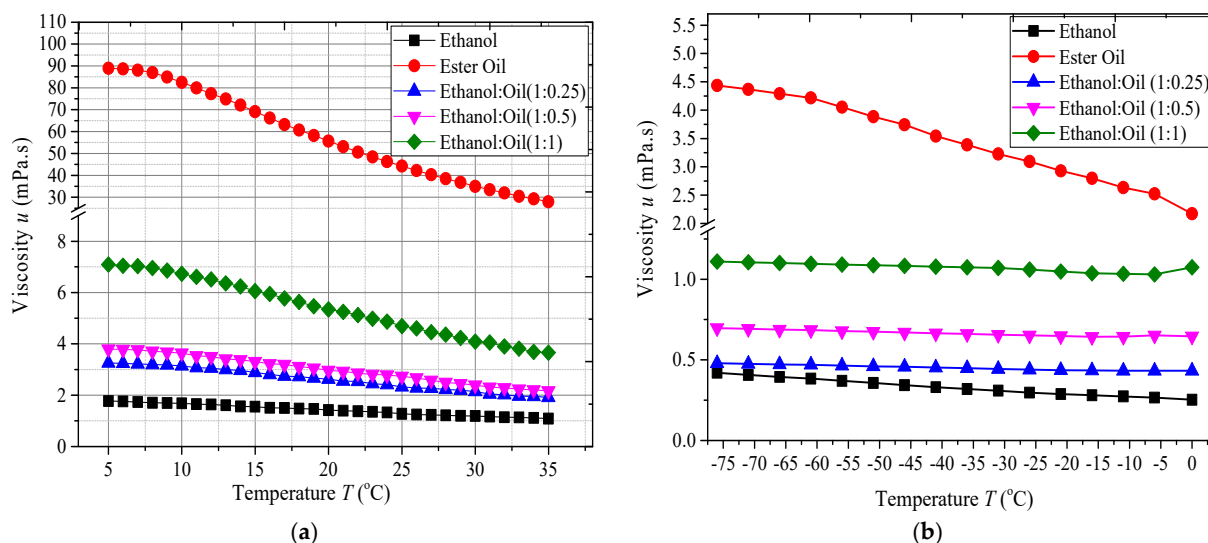


Figure 9. The viscosity of coolants/lubricants under variation in temperature. (a) No dry ice; (b) dry ice.

3.5. Evaporation

The evaporation rate of any coolant/lubricant at ambient temperature is significant. The evaporation rate should not be so high that it can evaporate earlier than the spray approaches the cutting zone to dissipate the heat. This is the reason why CO₂ performs well as a coolant in the cutting compared to liquid nitrogen. Therefore, the evaporation rate of this new cutting fluid was investigated at ambient temperature. Figure 10 shows that 110 g dry ice was placed in the ambient open air to find the evaporation rate. It shows a very smooth sublimation of dry ice from solid to gas form directly rather than converting to liquid. It shows a solid dry ice evaporation rate of 0.77 g/minute that is largely dependent on quantity, exposed area, and surrounding temperature. Similarly, a mixture of ethanol–dry ice illustrates a maximum flow rate of 2.37 g/min of evaporation, followed by ethanol–ester oil (1:0.25) with 2.27 g/min, ethanol–ester oil (1:0.5) with 2.14 g/min, ethanol–ester oil (1:1) with 2 g/min, and ester oil–dry ice with 1.32 g/min.

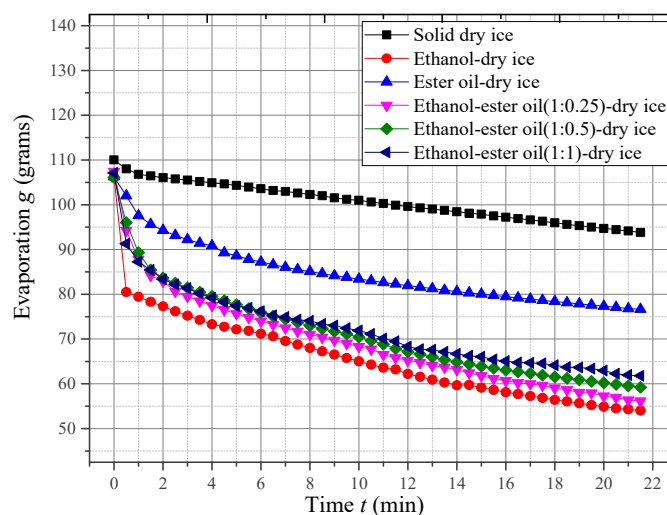


Figure 10. Evaporation rate of coolants/lubricants with respect to time.

Although the evaporation depends on the surface area and the quantities of liquid and dry ice, under a similar condition for each fluid, ethanol dissolved dry ice into gas quickly. The minimum evaporation rate of ester oil–dry ice can be associated with the agglomeration of dry ice in ester oil that did not dissolve rapidly into gas. Therefore, it is not a viable option to use only ester oil–dry ice for cooling.

4. Heat Transfer Characteristics of Coolants/Lubricants

This section describes the heat transfer setup and measurement of surface temperature, heat flux, and heat transfer coefficient under hybrid lubri-coolants.

4.1. Experimental Setup Details

The experimental setup is composed of six main parts, i.e., a double-walled cryogenic tank as a fluid reservoir, a nozzle, workpiece material, a high-speed camera, a heater, and a data acquisition system. The double-walled cylinder is made of stainless steel, having two inlets, one outlet, a safety valve, a pressure gauge, and a thermometer to display the temperature inside the cylinder. The outlet was connected to a pipe to the nozzle. The solid cone-type nozzle (diameter = 2 mm) was used to spray onto the workpiece surface. The nozzle was fixed at 20 mm from the workpiece top surface. A Ti-6Al-4V plate of approximately 4 mm thickness was drilled from the downside to insert the thermocouples. The distance between the two thermocouples was 12 mm. The thermal conductivity of the workpiece sample $k = 6.71 \text{ W/mK}$. The workpiece surface was heated, and then the fluid was sprayed onto the heated workpiece surface. The heat transfer with time was calculated to highlight the heat transfer under a mixture of ethanol–ester oil and dry ice blasting. The flow rate of 350~500 mL/h was kept constant throughout the experiments. Two K-type thermocouples were inserted at the bottom of the workpiece to measure the heat transfer. The thermocouples were integrated with a PerfectPrime (Model: TC41, USA) thermocouple thermometer ranging between -200 and $\sim 1372 \text{ }^{\circ}\text{C}$ ($\pm 0.2 \text{ }^{\circ}\text{C}$). The flow of the fluid was observed with a high-speed camera. Experiments were organized to investigate the mixture of ethanol–ester oil spray cooling with/without dry ice to determine the rate of heat transfer. Pure ethanol and ethanol–ester oil (1:0.25), (1:0.50), and (1:1) spray coolants were used as working fluids. The performance of ethanol and ethanol–ester oil mixtures with/without dry ice showed different heat transfer efficiencies. The schematic of the two-phase heat transfer is provided in Figure 11.

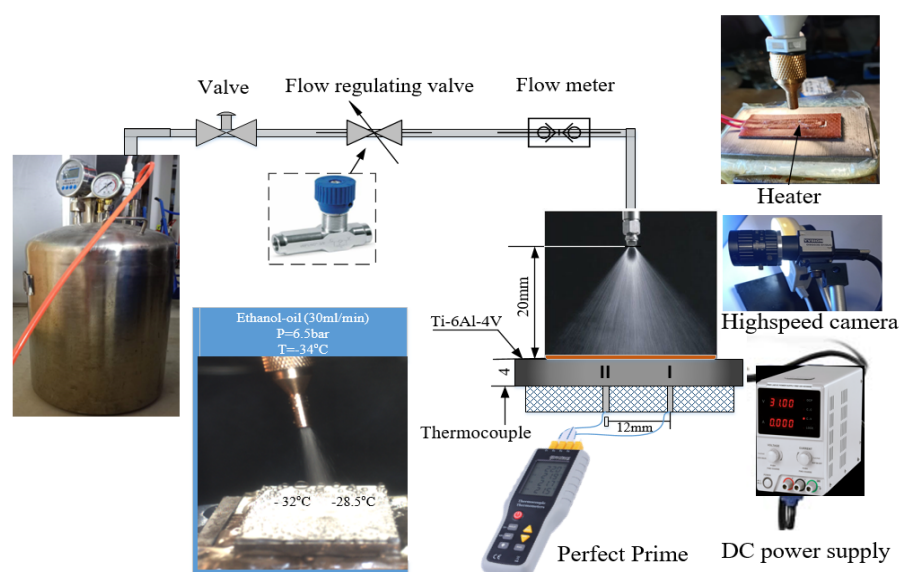


Figure 11. Experimental setup for measuring heat transfer coefficient.

4.2. Analytical Modeling

To find the heat transfer coefficient, a relation is defined in Equation (8) showing the heat transfer per unit time (Q) that can be determined on the workpiece surface and defined as [25]:

$$Q = C_p m \frac{dT}{dt} \quad (8)$$

where C_p and ' m ' are the specific heat and mass of the Ti-6Al-4V plate used in these experiments, respectively, while ' $\frac{dT}{dt}$ ' is the rate of temperature drop per unit time. In Equation (9), the mass m can be written as:

$$m = A\delta\rho \quad (9)$$

The mass of the plate ' m ' can be replaced in terms of thermal characteristics such as density ' ρ ', surface area ' A ', and the thickness (4 mm) of the plate ' δ ' in Equation (10). Therefore, by replacing the mass ' m ' in Equation (10), it could be rewritten as:

$$Q = C_p A\delta\rho \frac{dT}{dt} \quad (10)$$

By replacing the heat transfer rate (Q) into heat flux density $q = \frac{Q}{A}$, the formula could be rewritten in terms of heat flux:

$$q = -\rho C_p \delta \frac{dT}{dt} \quad (11)$$

where, ' ρ ' is the density of the workpiece plate ($4.4 \times 10^3 \text{ kg/m}^3$), ' C_p ' is the specific heat of 600 J/kgK , and ' δ ' is the thickness of the plate (4 mm). For the cooling rate, ' $\frac{dT}{dt}$ ' could be obtained by the differential quotient rule according to the temperature measured. Therefore, the heat transfer coefficient ' h ' could be obtained:

$$h = \frac{q}{(T_s - T_f)} \quad (12)$$

The surface temperature was also determined using the difference in temperature ' ΔT ' readings between two thermocouples; Δx is the known distance between thermocouples. The workpiece surface temperature T_s can be described by [25]:

$$T_s = T_{mean} - \frac{q\Delta x_{therm-surf}}{k} \quad (13)$$

Here, ' T_{mean} ' is the mean temperature of two thermocouples, and ' $\Delta x_{therm-surf}$ ' is the distance between the thermocouples and the workpiece surface.

4.3. Surface Temperature

Figure 12 shows the local temperature variation under the spray of 350 mL/h through a nozzle 2 mm in diameter. The ethanol, ester oil, and ethanol-ester oil (1:0.25), (1:0.5), and (1:1) with/without dry ice were sprayed onto a static plate surface. The nozzle was fixed near the workpiece surface (50 mm), and the coolant temperature at the nozzle exit was measured (coolant temperature). The nozzle exit temperature when spraying ambient temperature lubricants/coolants was 10.5°C , while the nozzle outlet of coolant with dry ice approached -25°C . The temperature measurements were taken for 11 min through thermocouples. The workpiece surface was heated by the heater, providing a constant voltage of 240 V and a corresponding current of 17.5 A. As the temperature approached 200°C , the nozzle spray was turned on to determine the surface temperature and measure the heat transfer coefficient. The only difference was that the temperature of the workpiece surface remained much lower due to dry ice that made the initial coolant temperature

-70.5°C . However, under dry ice MQL, due to a mixture of air and fluid, the nozzle outlet temperature approached -30°C . A rapid decrease in surface temperature can be associated with the liquid–vapor spray cooling, and the latent heat of sublimation led to superior heat transfer by striking the surface [22]. The surface temperature approached below zero after 110 s under all the coolants. After that, the temperature of the workpiece surface remained constant, reaching a minimum of -23°C under dry ice MQL [23]. Therefore, the impingement of dry ice reduced the temperature rapidly to -25°C within the first 100 s. Later, the rate of temperature decrease was slower up until 640 s.

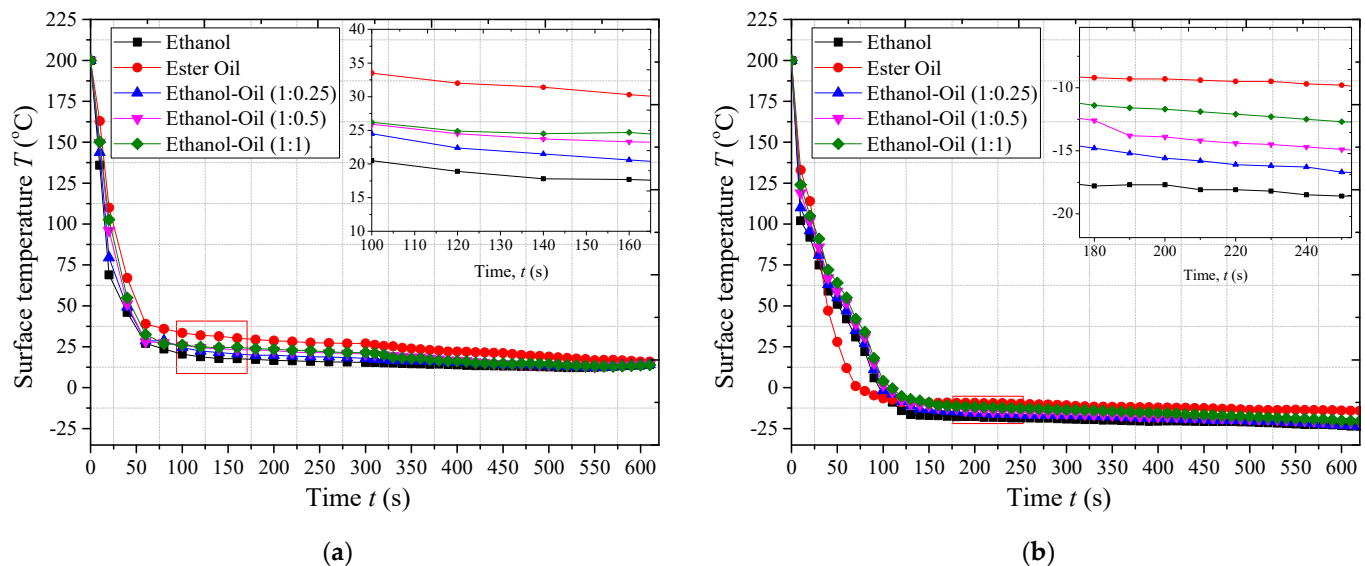


Figure 12. Surface temperature measured by spraying various lubri-coolants on a static plate. (a) No dry ice; (b) dry ice.

4.4. Surface Heat Flux

Figure 13 shows the cooling capability of the ethanol, ester oil, and ethanol–ester oil (1:0.25), (1:0.5), and (1:1) at ambient and dry ice temperatures (-78°C) directly associated in terms of heat flux under a specific time interval. It suggested that the heat flux ' q ' evolution of spray injection used to demonstrate, for a relatively long time, short pulse outcomes in terms of heat transfer per unit area. Two thermocouples were placed 12 mm from the applied spray. At constant flow conditions, ethanol showed a sudden decrease in heat flux from a maximum of 70.5 kW/m^2 to 15 kW/m^2 within the first 100 s. Moreover, from 100 s onward, a slow decrease in the heat flux was observed up until 600 s, and it remained steady until the end. Similarly, ester oil spray showed an exponential decrease in heat flux among the lubricant/coolants mentioned above. However, heat flux reduction was lower under ester oil than under ethanol and ethanol–ester oil concentrations. It is pertinent to mention that ethanol–ester oil (1:0.25), (1:0.5), and (1:1) show a similar trend of decreasing the heat flux with time. The maximum heat was observed under ethanol–ester oil (1:0.25) at 75 kW/m^2 , followed by ethanol at 70 kW/m^2 , 66 kW/m^2 under ethanol–ester oil (1:0.5), 65 kW/m^2 under ethanol–ester oil (1:1), and 46 kW/m^2 under ester oil. From this, it could be observed that a maximum heat flux in ethanol is associated with decreasing the temperature capability of the Ti-6Al-4V plate.

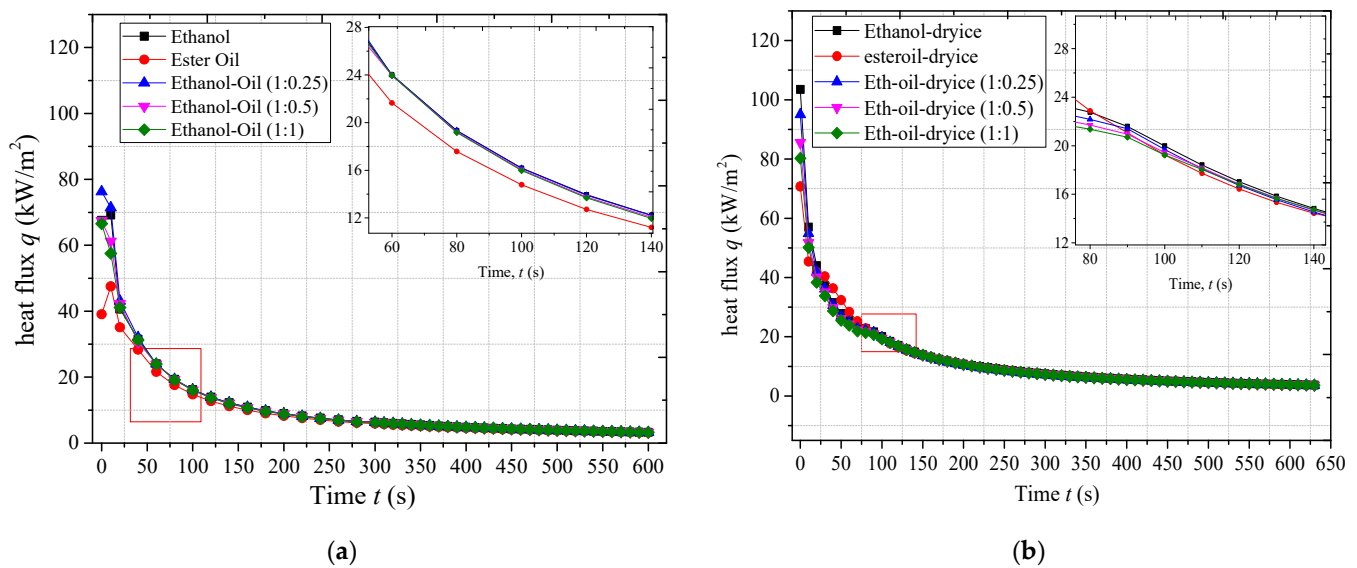


Figure 13. Heat flux under the spray of ambient temperature hybrid lubri-coolants. (a) No dry ice; (b) dry ice.

Spray cooling rapidly decreased the temperature and created a temperature difference leading to higher heat flux. Except for ethanol, all the curves follow a similar exponential trend of decrease in heat flux with time and become smooth after 450 s. Figure 13b shows the heat flux of ethanol, ester oil, and ethanol–ester oil (1:0.25), (1:0.5), and (1:1) as well as dry ice blasting. It could be seen that a rapid decrease in heat flux was observed under dry ice blasting. This rapid decrease was observed up to 15 kW/m² in the first 100 s and became smooth until 640 s. The maximum heat flux was obtained under ethanol at 103 kW/m², followed by ethanol–ester oil (1:0.25) at 96 kW/m², 85 kW/m² under ethanol–ester oil (1:0.5), and 70 kW/m² under ester oil. A rapid decrease in heat flux showed a decrease in the cooling performance of the already low-temperature surface. An instantaneous decrease in the heat flux was observed once cold hybrid lubri-coolant spray was started, as the cold molecules touch the surface, evaporate quickly due to the temperature difference, and remove the heat from the workpiece surface.

4.5. Heat Transfer Coefficient

Figure 14 illustrates the maximum heat transfer coefficient under ethanol, ester oil, and hybrid ethanol–ester oil (1:0.25), (1:0.5), and (1:1) under ambient temperature, as well as dry ice (−78 °C) cooling. It illustrates the heat transfer coefficient (h) under the spray of hybrid lubri-coolant ambient-temperature MQL. In the first 100 s, a rapid increase in (h) was found under all hybrid lubri-coolants. Later, it decreases linearly with the further increase in spray time. In the first 50 s, a rapid increase in (h) was found under all hybrid lubri-coolants. The maximum heat transfer coefficient (h) was 2962 W/m² C under ethanol–ester oil (1:0.25), followed by 2900 W/m² C under ethanol, 2950 W/m² C for ethanol–ester oil (1:0.5), and 2900 W/m² C under ethanol–ester oil (1:1). Furthermore, a minimum heat transfer coefficient of 2750 W/m² C was observed for the ester oil.

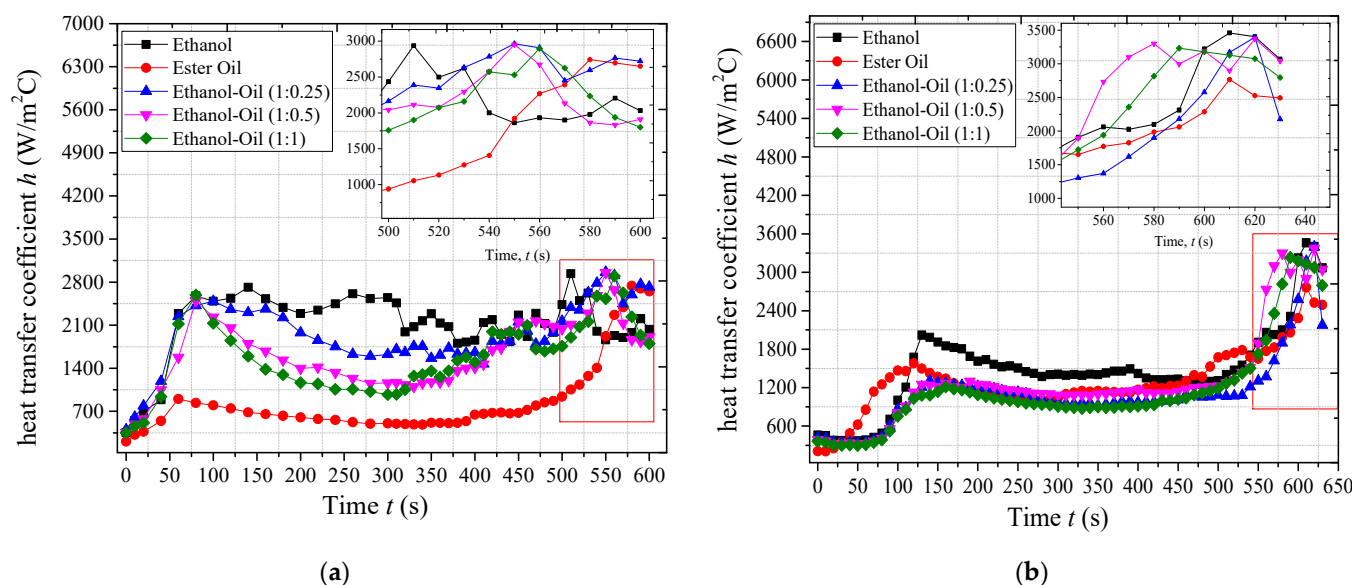


Figure 14. Heat transfer coefficient under hybrid lubri-coolants. (a) No dry ice; (b) dry ice.

From the analysis, it could be better understood that heat removed from the surface is a function of the time duration of spray injection (Δt) [26]. The heat transfer ability of dry ice coolant/lubricant is higher than that of ambient temperature coolants sprayed onto a flat surface for specific spray injection time. The maximum heat transfer of ethanol at ambient temperature is 2900 W/m² C, and under ethanol–dry ice hybrid lubri-coolant, it is 3400 W/m² C. It could be said that ethanol–dry ice hybrid lubri-coolant has a 17% increase in the heat transfer coefficient compared with ethanol spray at ambient temperature. In a typical thermal analysis of spray cooling, a two-phase spray for efficient heat transfer performs well by removing the heat from the specific region. The results presented here depict their prominent heat transfer and their thermal management, which are encouraged to be implemented in machining.

5. Machining under Hybrid Ethanol–Ester Oil–Dry Ice

A rectangular heat-treated workpiece material of Ti-6Al-4V (200 mm $\times$ 105 mm $\times$ 20 mm) is milled by DMU-60 DMG MORI, a five-axis milling center having a spindle speed of 20,000 rpm, a maximum power of 25 kW, and a maximum feed of 50 m/min. The measurement of tool flank wear was carried out using an optical microscope. The milling experiments were carried out at cutting speeds 75, 150, 225, and 300, feed per tooth 0.04 mm/z, width of cut a_e = 8 mm, depth of cut a_p = 0.5 mm, and tool diameter D_t = 25 mm. The hybrid ethanol–ester oil was pre-mixed in a double-walled cylinder. The exit of the cylinder was attached to the MQL nozzle. Considering the machining conditions, the minimum quantity lubrication (MQL) was used at a constant pressure of 6 bar and flow rate of 350 mL/h. The MQL nozzle diameter was 2 mm and fixed 25 mm from the cutting zone. Figure 15 shows the machining setup to perform the experiments.

Cutting Tool Life under the Cooling Condition

It is a well-known fact that there is a direct correlation between cutting temperature and cutting speed [27]. At high cutting speed, a coolant/lubricant fails to reach the cutting zone, and a high rate of material deformation converts into an elevated temperature that damages the tool life. As shown in Figure 16, a comparison of cooling environments' effects on tool life was carried out at the same cutting speed. The increase in cutting speed from 75 to ~300 m/min under ambient temperature MQL (ethanol, ester oil, ethanol–ester oil) and dry ice MQL (ethanol–dry ice, ester oil–dry ice, ethanol–ester oil–dry ice) results in shorter tool life.

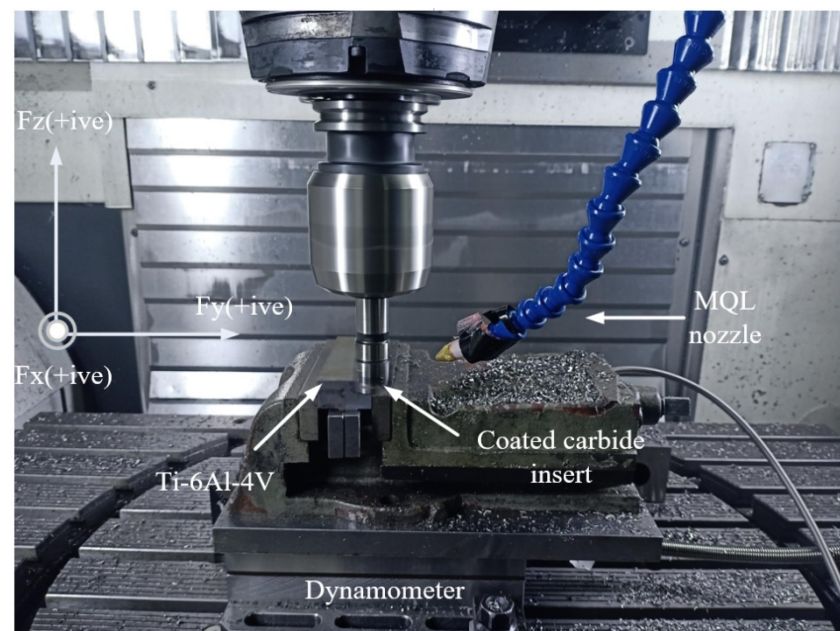


Figure 15. Experimental setup of milling Ti-6Al-4V.

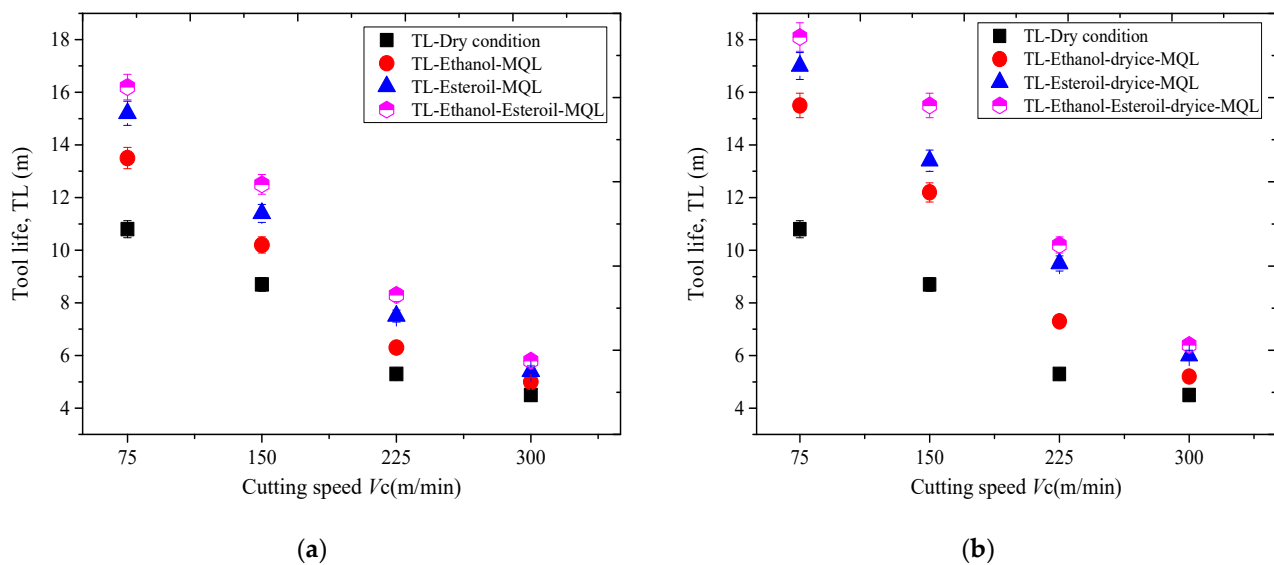


Figure 16. Tool life in terms of cutting length (m) under hybrid lubri-cooling. (a) No dry ice; (b) dry ice.

Figure 16a depicts the effect of cutting speed on tool life under ethanol, ester oil, and ethanol–ester oil MQL cooling environments. The maximum tool life reaches (before tool discarding) a maximum of 500 μm wear on the main cutting edge. At a low level of cutting speed (75 m/min), ethanol–ester oil MQL provided the maximum tool life of almost 16.2 m, followed by ester oil with 15.2 m and ethanol with 13.5 m, as well as a minimum of 10.8 m under dry conditions. Similarly, at a high level of cutting speed (300 m/min), the tool life was 5.8 m under hybrid ethanol–ester oil and a minimum of 4.5 m under dry conditions. This indicates the effect of coolant/lubricant on milling Ti-6Al-4V, where the heat generated during machining was effectively removed under hybrid lubri-cooling and ester oil MQL. At high cutting speed, the ethanol–ester oil evaporated and provided lubrication at the same time. Although the very high temperature was generated at high cutting speed, long-chain ester oil consists of stearic (C17 H35 COOH), oleic (C17 H33 COOH), and linoleic fatty acids (C17 H31 COOH) sustained under high pressure and helps

to generate tribo-film on the workpiece and cutting tool. Therefore, high heat transfer and lubrication helped to generate discontinuous and curly chips to prevent chip adhesion on the tool cutting edge.

Figure 16b shows tool life under varying cutting speeds under ethanol-dry ice, ester oil-dry ice, and ethanol-ester oil-dry ice MQL. The effect of dry ice lubricant/coolant on tool life under different cutting speeds showed the hybrid ethanol-ester oil-dry ice having a maximum of 18.1 m, followed by ester oil-dry ice at 17 m, 15.5 m under ethanol, and 10.8 m under dry conditions. At high cutting speed (300 m/min), the maximum tool life was 6.4 m under hybrid ethanol-ester oil-dry ice, 6 m under ester oil, 5.2 m under ethanol-dry ice, and 4.5 m under dry conditions. At low cutting speed, the dry-ice-assisted MQL with a high heat transfer coefficient dissipated the heat, resulting in improved hardness of the cutting tool. Therefore, less wear was observed under low cutting speed. However, at high-speed machining, high heat generates due to friction and plastic deformation, and there is a lower chance of approaching the coolant at the cutting zone to dissipate the heat [28]. At high cutting speed, the role of lubrication was also significant in controlling heat generation and tool wear. Zhang et al. [29] have reported that minimum quantity cooling lubrication sprays tiny drops of mist that penetrate well at the cutting zone. This small-sized particle mist provides enough of the long-chain ester oil and ethanol -OH group that provide lubrication. MQL can effectively lubricate the cutting zone at low and moderate cutting speeds and reduce the heat generation due to the friction at the secondary and tertiary deformation zones. However, further increases in cutting speed diminish the effectiveness of MQL cooling and lubrication at 300 m/min.

6. Conclusions

The ethanol, ester oil, and ethanol-ester oil (1:0.25), (1:0.5), and (1:1) with dry ice and without dry ice samples are prepared and evaluated regarding their thermophysical properties (density, specific heat, thermal conductivity, and viscosity), tribological properties (friction coefficient, friction force), and thermal properties by spraying coolant/lubricant mist on a hot static plate to evaluate heat dissipation (surface temperature, heat transfer coefficient, heat flux). The trial runs on the milling machine were carried out to decide further research on hybrid lubri-cooling. Important conclusions are drawn based on these parameters:

- Thermophysical properties vary with temperature change. *Without dry ice*, the density (g/mL), thermal conductivity, and viscosity decrease, while specific heat increases in temperature from 5 °C to 30 °C. *With dry ice* (−78 °C), the temperature increased from −76 °C to 0 °C, and density (g/mL) was increased until −25 °C and then remained constant until 0 °C. While thermal conductivity and viscosity decreased, specific heat increased with the increase in temperature from −76 °C to 0 °C. Therefore, the addition of dry ice overall reduced the density, specific heat, and viscosity, while it increased the thermal conductivity.
- A significant increase in the heat transfer coefficient was observed under lubri-coolants sprayed onto a static hot plate. The addition of dry ice increased the heat transfer coefficient by 17% for ethanol, 11.4% for ethanol-ester oil (1:0.25), 8% for ethanol-ester oil (1:0.5), 5% for ethanol-ester oil (1:1), and a minimum of 2% for ester oil. It can be said that increasing the proportion of ester oil in hybrid ethanol-ester oil reduced the heat transfer coefficient.
- In the machining of heat-treated Ti-6Al-4V, the addition of dry ice into hybrid ethanol-ester oil increased the tool life up to 11.5% at a low level of cutting speed, while at a high level of cutting speed, ethanol-ester oil-dry ice improved tool life up to 10%. A maximum improvement in tool life was obtained under hybrid ethanol-ester oil-dry ice among all conditions.
- The obtained results of this study are useful to manufacturing engineers for assessing a newly developed coolant behavior. This hybrid ethanol-ester oil is sustainable and one step towards sustainable manufacturing in the Chinese manufacturing industry (CMI).

The key benefits of this hybrid ethanol-ester oil–dry ice are green, environmentally friendly, economical, and useful applications of CO₂ as a byproduct of chemical industry.

7. Limitations and Future Work

There are numerous challenges to the data collection, i.e., difficulties in obtaining cutting temperature data using thermocouples as well as making a special data cylinder to mix dry ice, ethanol, and ester oil. Additionally, there is a need to apply regression analysis to find relations between temperature change and thermophysical properties, as well as a need to perform multi-objective optimization using heuristic techniques. The impact of the proposed technique on workers' safety and health will also be studied in the future. Sustainable production in terms of energy, carbon emissions, cost analysis is out of the scope of the study and will be discussed in future research. Pressure head losses in the cryogenic tank will also be considered in the future. Besides, using the same methodology, a case study will be carried out for other materials to obtain information for resource consumption in real time.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

EPA	Environmental Protection Agency
MQL	Minimum quantity lubrication
LN ₂	Liquid nitrogen
k (W/mK)	Thermal conductivity
μ (mPa.s)	Viscosity
TPS	Transient plane source
τ (Pa)	Shear stress
γ (1/s)	Shear strain rate
m	Mass of the Ti-6Al-4V plate
A	Surface area
cryoMQL	Cryogenic minimum quantity lubrication
MP (°C)	Melting Point
BP (°C)	Boiling point
C_p (kJ/kgK)	Specific heat
ρ (g/mL)	Density
DSC	Differential scanning calorimeter
u (mPa.s)	Viscosity
Q	Heat transfer per unit time
$\frac{dT}{dt}$	Temperature drop per unit time
δ	Thickness of the plate

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