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# Environmental Generation of Cold Air for Machining

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## Abstract

Traditional flood cooling for many companies still remains the preferred method of cooling the cutting zone, even though researchers have shown that using cold air can be a feasible alternative. Providing an energy efficient cooling method needs to be a prime concern for achieving sustainable metal cutting. The objective of this research is to determine the most effective generation of cold air for use during the machining operation. Environmentally-conscious companies are now practically demonstrating that the use of cold air as coolant reduces their disposal costs, and can increase the value of the produced swarf. Technical feasibility of three cold air generating methods will be reviewed, and a sustainability implications of the use of different coolants have been discussed.

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*Keywords:* Flood cooling; energy efficient cooling; cold air; vortex tube; thermoelectric cooling; lowest environmental impact

## 1. Introduction

Since the beginning of the 20th Century liquid coolant has played an important role in the machining process. It is used to reduce cutting temperatures and also lubricates the cutting process. Environmental concerns now dictate that cutting fluid needs to be disposed of in a sustainable manner, resulting in traditional coolant contributing 16-20% of the manufacturing costs. In addition, various studies have revealed that the coolant can also cause health problems [1-4]. However, cutting fluid cannot simply be eliminated from the machining processes since high temperature, caused by the cutting process, still needs to be reduced to prolong the tool life, and to maintain the quality of the surface finish of the product. Many companies are seriously looking for an alternative sustainable cooling method.

Many companies have adopted cold air (CA) as an alternative cooling method, having varying degrees of success in replacing traditional cutting fluid. A number of studies have been carried out detailing the benefits of cold air in assisting machining processes. However, very few discuss the aspect of generating an environmentally cold air supply for the cooling of the tool tip. Three methods which will be discussed that can produce cold air to be used to cool the cutting zone: vortex tube (VT), thermoelectric cooling (TEC) and cryogenic cooling using compressed air (CCA). In practical terms, for refrigeration, it is important to determine the coefficient of performance (COP) of the VT, TEC and CCA when comparing their effectiveness. These methods may also be contrasted against a conventional refrigeration (COP) in determining the efficiency of cooling. The practicality of these cooling methods when machining must also be considered in determining the best cooling method.

There have been a number of environmental burden and sustainability assessment methods developed in order to minimise the effect of manufacturing on the globe [5, 6]. These methods include Life Cycle Analysis (LCA), Life Cycle Impact Assessment (LCIA), and Design for the Environment [7-10]. Eco-Indicator 99 can also be used to determine the impact of emissions to human beings and ecosystems in determining the global warming potential [11]. This analysis identifies the total energy intensity of the whole process, resulting in a more complete assessment of energy used for an organisation, recognising the major energy elements of the cooling process, e.g. air compressor. Eliminating the use of traditional wet cooling with efficient cold air generation will vastly reduce the metal cutting burden on the environment.

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## 2. Vortex tube

The VT as shown in Figure 1 has been used for many years by many manufacturing organisations to produce cold air for spot cooling and machining as it only requires compressed air. The VT has a number of advantages including its ability to produce reasonably low temperature (as low as -40°C), and it is maintenance free as there are no moving parts. However, there is a fundamental challenge with its operation. It requires a high air flow rate (as shown in Table 1) and large capacity compressor to support the cooling effect of the VT.

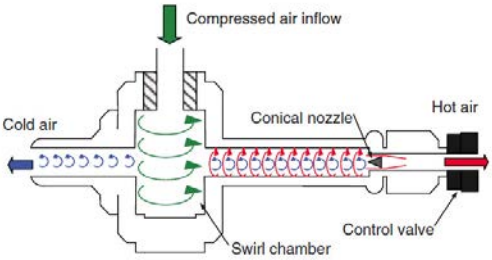

Fig. 1. Typical vortex tube [12]

It may be noted that opposite to what is normally viewed in thermodynamics, the VT may be considered as an open control volume device. If the system is assumed to be steady state, then from the first law of thermodynamics we can have:

$$\Delta\dot{H} = \dot{Q} \tag{1}$$

The VT system enthalpy change $\Delta\dot{H}$ and $\dot{Q}$ is the heat exchanged between the system and its surroundings. Assume that $\dot{Q}$ is approximately zero even though the cold tube may have frost on it and the hot tube is very warm. If this is the case:

$$\Delta H = \Delta H_c + \Delta H_H = 0 \tag{2}$$

where $\Delta H_c$ is the enthalpy change of cold stream and $\Delta H_H$ is the enthalpy change of hot stream. Assuming that air is an ideal gas, the total enthalpy change can be written as:

$$\Delta H = m_c C_p (T_c - T_i) + m_h C_p (T_h - T_i) = 0 \tag{3}$$

$m_c$ is mass flow rate at cold tube, $m_h$ is mass flow rate at hot tube, $T_c$ is cold air temperature, $T_i$ is inlet air temperature, $T_h$ is hot air temperature and $C_p$ is specific heat of air at constant pressure. Assuming the process as reversible and adiabatic, and by applying the second law of thermodynamics to this system, it estimates the coefficient of performance (COP). Focusing on the cooling effect that can be achieved by placing the cold pipe within an enclosure, the COP can be calculated:

$$\mathrm{COP} = \frac{\Delta\dot{H}_c}{\dot{W}} \tag{4}$$

$$\Delta\dot{H}_c = \dot{m}_c \, C_p (T_i - T_c) \tag{5}$$

$\Delta H_c$ is equal to the heat that is transferred to the cold stream through the cold pipe wall (like a heat exchanger) source, and $\dot{W}$ in the this case is the work done to compress the air from atmospheric pressure and temperature to the inlet conditions of the VT. Assuming reversible compression (isentropic, minimum work) $\dot{W}$ obtained from:

$$\dot{W} = \frac{\dot{m}R(T_2 - T_1)n}{n-1} \tag{6}$$

where $T_2$ is the compressor exit temperature, and $T_1$ is the compressor inlet temperature (reversible, polytropic process; air: n=1.4). If we consider a complete system, $P_1$ and $T_1$ are the atmospheric pressure and temperature, $P_2$ and $T_2$ are the compressor exit conditions.

$$\frac{P_2^{\frac{n-1}{n}}}{P_1} = \frac{T_2}{T_1} \tag{7}$$

After the air is compressed, it is kept in the high-pressure tank where then it cools down to the atmosphere temperature $T_1$, so the inlet temperature of the nozzle $T_i$, is equal to $T_1$. By noting that:

$$\frac{\mathrm{Rn}}{\mathrm{n-1}} = C_p \tag{8}$$

Equation (6) can be simplified to

$$\dot{W} = \dot{m}_i C_p (T_2 - T_i) \tag{9}$$

with $T_2$ calculated from equation (7). This is an ideal work value so it is less than the actual work needed to drive the compressor.

Table 1. Typical VT operating measurements

| Parameter | Value |
|---|---|
| Cold Mass Fraction | 0.605 |
| Inlet Temperature (˚C) | 22.4 |
| Cold Outlet Temperature (˚C) | -16.8 |
| Hot Outlet Temperature (˚C) | 66.6 |
| Inlet Volumetric Flow Rate (SLPM) | 1095 |
| Hot Outlet Volumetric Flow Rate (SLPM) | 425 |
| Cold Outlet Volumetric Flow Rate (SLPM) | 651 |

By considering the above equations and using the equation (4), the COP of the VT can be determined. From data recorded in tests it was established that a VT with a 3 mm diameter cold outlet with an inlet air pressure of 0.275MPa provided a suitable cold air nozzle temperature as given in Table 1.

For this application of the VT the COP was found to be 0.173 which is considerably less than an average refrigerator which is approximately has a COP of 3.

## 3. Thermoelectric cooling

This paper discusses the use of thermo-electric cooling (TEC) to produce cold air to be used in the machining process. Thermoelectric method has been applied in various fields ranging from medical equipment to the military equipment, not only as cooling equipment, but also as a power generator. The main requirement to be met is the temperature of cold air: its flow rates should be able to cool the tool contact with the workpiece.

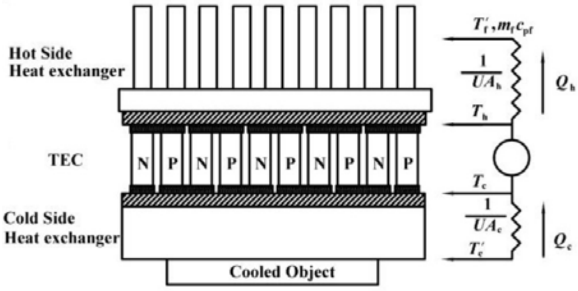

Fig. 2. Typical TEC schematic diagram [13]

The size of thermoelectric modules ranged from approximately 2.5-50mm square with height 2.5-5mm [14]. The relatively small size and weight of the TEC allows this system to be easily applied in the metal cutting process. It has no moving parts, the temperature of produced cold air can be controlled precisely. It will be more environmentally friendly since it doesn't use or produce any gases [15].

A small prototype system was produced as shown in Figure 3, and used eight TEC1-12706 thermoelectric cells to determine its possible feasibility. The specification for each thermoelectric cell is given in Table 2.

Table 2. Model Number TEC1-12706 Specification

| Parameter | Value |
|---|---|
| Dimensions (mm) | 40 x 40 x 3.8 |
| Voltage (V) | 12 |
| U max (V) | 15 |
| I max (A) | 6 |
| Q max (W) | 72 |
| Temperature Difference (˚C) | 65 |
| Power drawn (kW) | 0.036 |

Air was supplied to the inlet of heat transfer by using a small centrifugal pump. The air flow rate was controlled by varying the currents received by the pump motor. Maximum power of 12V and 4A per TEC module was supplied to a pair of TEC modules in parallel configuration. Thermocouples were used to measure TEC cold side, fin heat sink, copper tube temperature, nozzle outlet temperature and ambient temperature.

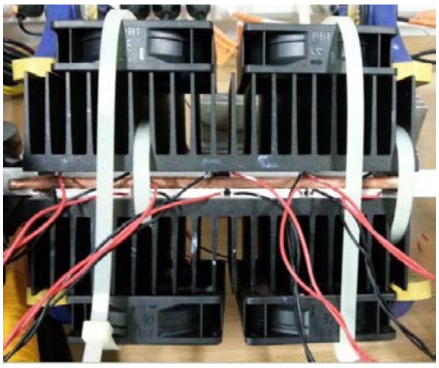

Fig. 3. Thermoelectric air cooler

For the thermoelectric air cooler the estimated coefficient of performance (COP) focusing on the cooling effect of the TEC with respect to the amount of electrical power needed to supply the cold air. The COP can be calculated by equation (4) and the heat transfer rate can be obtained from:

$$Q_c = UA_c(T'_c - T_c) \tag{10}$$

where $Q_c$ is the heat transfer rate, and $UA_c$ is the overall thermal conductivity from the cold junction to the interface between the cooled object heat. If we consider $T_c$ as the cold side of the TEC and $T'_c$ the cooled object. The heat transfer rate can be redefined for the TEC system as:

$$Q_h = {}^{\varepsilon}{}_{h} m_f C_{pf}(T_h - T'_f) = m_f C_{pf}(T''_f - T'_f) \tag{11}$$

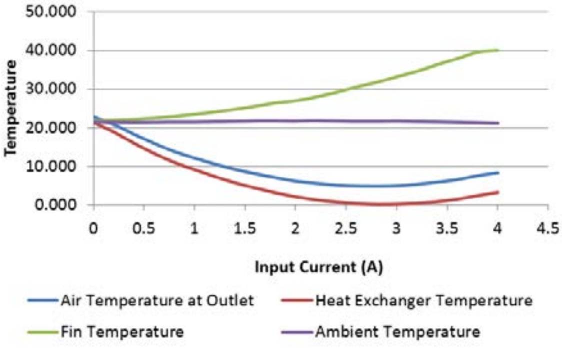

Fig. 4. TEC air cooling temperatures

It was found from this prototype TEC air cooler that at output air speed of the air cooling system provided air between

2m/s and 4m/s; for a corresponding current of 3A to 5.75A respectively as shown in Figure 4.

For simplicity, the heat transfer rate can also be obtained from:

$$Q_c = (S_M\ x\ T_c\ x\ I) - \left(0.5\ x\ I^2\ x\ R_M\right) - (K_M\ x\ D_T) \tag{12}$$

where $S_M$ is Seebeck coefficient of the module, I is the input current to the module, $R_M$ is the electrical resistance of the module, $K_M$ is thermal conductance of the module and $D_T$ is temperature difference ($T_h$ - $T_c$).

For this application of the thermoelectric air cooler the COP was found to be 0.011 which in first instance looks inferior to the VT. However, the COP of the prototype thermoelectric air cooler can be improved with some modifications.

## 4. Cryogenic cooling compressed air

Liquid Nitrogen ($LN_2$) can be used to cool the machining process by spraying $LN_2$ directly to the cutting zone. Various studies have shown that this method can improve the performance of the machining process. However, extremely low temperature makes handling and application of $LN_2$ hazardous, and precautions need to be taken. $LN_2$ can cause "cold burns" to unprotected skin coming in contact with $LN_2$ or uninsulated cold equipment. Typically exposed skin may stick fast with the flesh being torn off on removal. In addition, increased levels of nitrogen due to the evaporation process (gas expansion) can also cause lack of oxygen for machine operators. During the application of cryogenic cooling a machine operator should wear special cryogenic Personal Protection Equipment, and the machining work space must be well ventilated.

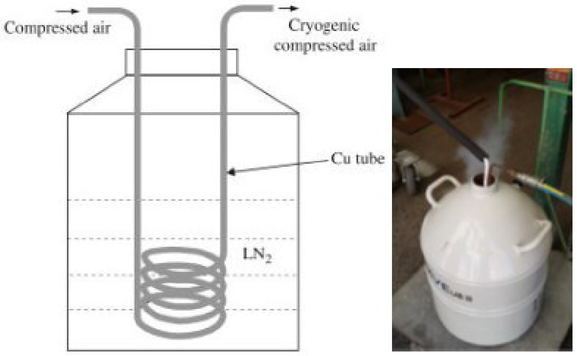

Fig. 5. Cryogenic cooling compressed air [5]

In this experiment $LN_2$ was used to obtain cold air that will be applied to cool the machining process as shown in Figure 5. Publication by Sun et al showed that the cryogenically cooled air method is safe, easy to apply and also capable of generating high air flow rates with very low temperature [16]. Cold air acquired by passing compressed air through a heat exchanger (a coil of copper tube) submerged in the Dewar flask containing $LN_2$. The presence of moisture in the compressed air will crystallise and block the copper tube. For this reason it is essential that an air dryer is incorporated in the air supply line.

In this experiment 5.5bar pressure air was supplied to the inlet section of copper tube. The results from each test showed that after three minutes coil submerging the temperatures of produced cold air was under -70°C. Constant temperature below -80°C was achieved until the ninth minute. For each test the cold air flow rate ranging between 41m/s and 45m/s.

During the test the flow rate of cold air was reduced significantly after 10 minutes coil submerging. This occurs due to the tube blocked partially by the crystallised moisture. However, total blockage has never happened in this experiment. Ideally, by supplying moisture free compressed air at the inlet of the copper coil, tube blockage can be avoided and cold air can be produced continuously.

Table 3. Estimated energy consumption by each minute

| Time (min) | Evaporated $LN_2$ (kg) | Energy consumed per weight (kWh/kg) | Energy consumed in cooling (kWh) | Outlet temperature (C) |
|---|---|---|---|---|
| 1 | 0.24 | 0.5 | 0.12 | -60.3 |
| 2 | 0.48 | 0.5 | 0.24 | -69.3 |
| 3 | 0.72 | 0.5 | 0.36 | -71.7 |
| 4 | 0.96 | 0.5 | 0.48 | -73.7 |
| 5 | 1.2 | 0.5 | 0.6 | -73.3 |
| 6 | 1.44 | 0.5 | 0.72 | -74.7 |
| 7 | 1.68 | 0.5 | 0.84 | -76 |
| 8 | 1.92 | 0.5 | 0.96 | -76.3 |
| 9 | 2.16 | 0.5 | 1.08 | -77.7 |
| 10 | 2.4 | 0.5 | 1.2 | -82.3 |

Energy requirement for cryogenic compressed air was a combination of compressor energy to supply compressed air and the energy required to produce $LN_2$. According to Knowlen, $LN_2$ mass production by commercial plant requires energy around 0.5kWhr/kg [17]. With an average weight reduction of 0.24kg per minute, the energy consumption during the 10-minute test can be calculated (Table 3). Based on the evaporation of $LN_2$, the energy required to produce cryogenic compressed air for 10 minutes was 720W. For this application the COP was found to be 1.58, which in first instance looks the best cooling system. However, this COP was based only on the evaporation of the used $LN_2$ and not on the energy needed to provide the $LN_2$.

## 5. Sustainability implications of cold air for machining

Whilst cold air cooling systems completely avoid the need for liquid coolants, it is not carbon neutral due to energy intensive cooling process. In the case of cryogenic compressed cold air cutting systems, cooling itself consumes about 0.12kWh of electricity per minute, which is 33% and 28% higher than the total energy consumption by traditional flood cooling and minimum quantity liquid systems respectively [18, 19]. Therefore, carbon footprint is expected to increase due to this cold air cooling system.

Some other associated environmental impacts such as human toxicity and euthrophication that are directly related to the use of liquid coolants, can potentially be mitigated due to use of cold air cutting system. Apart from environmental impacts, there are also health associated social impacts. The cutting fluids become contaminated with heavy metals and aerosols during use which can affect skin and respiratory systems. Also used coolant has been found to be the breeding ground of fungi and living organisms.

There are economic benefits associated with the replacement of traditional flood coolant with cold air cooling or MQL. Even though energy cost could be increased by 20 cents for machining a workpiece when using cold air or MQL. These cooling methods will all give significant saving from the avoidance of coolant (80 cents per workpiece) [18]. Improved cold air production is essential in reducing the environmental impact and economics of air cooling cutting tools.

## 6. Conclusion

Cold air cooling when combined with MQL has shown to provide companies with an effective environmental solution to eliminating flood coolant. This paper excluded the operational aspects of MQL as the air cooling element contributed the major energy burden in cooling the tool interface. The VT is commonly used for providing cold air. However, as shown from previous test results, the VT is quite inefficient. The small TEC prototype cooling system was trialled to see if enough cold air could be generated using less energy than the VT, and in a convenient manner. The third cooling approach using $LN_2$ to cool the compressed air proved to be very effective at cooling the air. Unfortunately, required enormous amounts of energy to provide $LN_2$, and was subject to practicalities in use. It is apparent that the COP for the VT and TEC were very low when compared to the $LN_2$ produced cold air. This can be instigated by the fact that these systems are dynamic in the production of cold air in contrast to the $LN_2$ method in providing cold air. Although the COP of the TEC was found only to be 0.011, further work on the TEC prototype system would improve the COP making it a more practical method to be part of a machine tool. Eliminating the use of traditional cutting fluid makes cold air cooling more environmental friendly for cooling the tool tip. Further environmental improvement can be achieved by using the most sustainable cooled air generating method. This research suggests that cold air generated by the TEC will be more energy efficient and more convenient to use, as it will eliminate the need for large volumes of compressed air used by the VT.

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