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High precision thermal control of fluidic mediums

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Abstract

Thermal issues remain amongst the primary sources of error in modern mechanical machinery, especially in the high and ultra precision regimes. Managing the thermal changes on a machine to maintain stability over long periods of time can prove to be very challenging. It is also much more difficult to control the temperature of oils compared with water, as oils are relatively insulating, and heat will transfer less efficiently through the oil. This research project studied the effects of a system designed to take any given fluid, primarily focused on oils and water-based coolant, and control said fluid to a given temperature ± 0.01°C, where the given temperature suits the application. The Thermal Control Units (TCUs) designed as part of the project had a few other constraints to make them more suitable for general applications, such as being able to handle up to 100 bar of pressure, and being able to handle the largest flow rates possible for given fluids. The TCUs primary usage is as a trimming device, where the fluid is controlled by a chiller, usually in the ± 0.3°C range, which is often done with heat exchangers.

The TCUs have held water-based process coolant to ± 0.01°C, over a period of 18 hours, at flow rates exceeding 20 l/min, with future versions scaling this to double in a single unit, and the capability to utilise multiple units in parallel to achieve greater total flow rates. The TCUs have been used on ultra precision machines, holding temperatures to ± 0.01°C, at flow rates over 10 l/min for days at a time, with further testing required to determine how much more flow rate would be attainable for a single unit, with typical thermal disturbances.

Thermal control, thermal issues, oils, coolant

1. Introduction

It has been reported [1] that up to 75% of geometric workpiece errors can be attributed to thermal issues and that up to 60% of a machine's power consumption can be attributed to thermal control. With advances and innovations in technology, the drive to manufacture smaller and more precisely is becoming even more critical. With the requirements being tighter tolerances, surface finishes, forms etc., thermal issues become magnified and become a much more critical issue to remove.

Complex (and variable) machine thermal loops present significant machine stability issues, but even considering a simple example of a typical spindle shaft with a distance of 100 mm between the thrust bearing and the tool will grow 120 nm with a change in shaft temperature of +0.1 °C [see *Figure 2*], consuming a significant percentage of the error budget when for example, machining optical components with sub-micron form error tolerances. Controlling the shaft temperature to +0.01 °C would reduce spindle growth to 12 nm [see *Figure 2*]. Thus, more reliable methods are required for controlling temperature, either over specific circuits, or an entire machine.

Existing temperature control systems typically consist of vapor-compression systems that remove heat from a liquid via an intermediate refrigerant. Typically, these struggle to get below ±0.1 °C without drastically increasing both the cost and the size of the unit.

A unit was schemed and designed for initial testing, with the design evolving over the years to account for the results and outcomes obtained through testing. Multiple units can be used in parallel, as long as the in-built temperature probes for each unit are all calibrated relative to each other.

The units are usually utilised as a trimming device with a bulk chiller acting in front of them, usually in the form of a heat exchanger, typically in the range of ±0.1 °C, which remove any and all of the aggressive coolant temperatures in the system, such as those generated through machining operations.

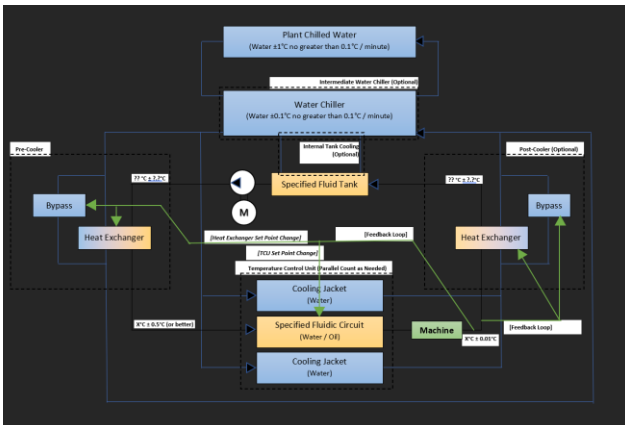


Figure 1. Example circuit diagram.

$$0.1m \text{ x } 12\,\frac{\mu\text{m}}{\text{m}.\,°\text{C}} \text{ x } 0.100°C \; = 120nm$$
$$0.1m \; x \; 12\,\frac{\mu m}{m.\,°C} \; x \; 0.010°C \; = 12nm$$

Figure 2. Thermal growth calculations.

2. Methodology

One medium that is commonly used across the manufacturing world is oil, which has a much lower heat transfer coefficient (VG10 ≈ 0.130 W/(m.K)) than water (0.6 W/(m.K)). After CFD simulations, it was shown that for any reasonable flow of oil past a highly conductive wall at a different temperature to the medium, the temperature would penetrate efficiently to a maximum depth of 1 mm from the wall.

This lead to the thinking that if a balance could be obtained between holes small enough to maximise the thermal transfer, but large enough to minimise pressure drop, then a pattern of holes in a highly thermally conductive block could lead to an optimal heat transfer into a medium. Combined with Thermo-Electric Devices (TEDs), which are a solid state, rapid response device that can provide both heating *and* cooling, a device was designed to this effect.

2.1. The Temperature Control Unit (TCU)

The design was originally based around a block with as many 3mm diameter holes as it was feasible to package into a given area, as 3mm gave a good balance between the thermal penetration [see **Figure 3**] and pressure drop. The higher the total count of holes, for a given total flow rate, the lower the individual hole flow rate (and therefore time spent in each hole), and the more surface area for the medium to be in contact with the walls. Longer drilled holes lead to an increase in the surface area and time spent in the holes, but increase the pressure drop.

The holes are always drilled in a way that they end in a cross-directional large bore [see **Figure 3**] so that any wandering drills from the starting surfaces do not cause any issues other than fractional reductions in the utilisable metal cross sectional area.

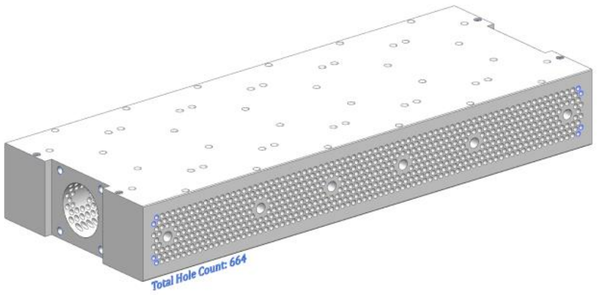


Figure 3. TCU primary block.

On the upper and lower surfaces of the block, are the TEDs, which give the rapid response heating and cooling as required by the system [see *Figure 4*]. The polarity of the current supplied to the TEDs will cause the unit to change between heating and cooling, and the unit can therefore react much more quickly, where required, that a conventional temperature control system that is focused on only heating or cooling.

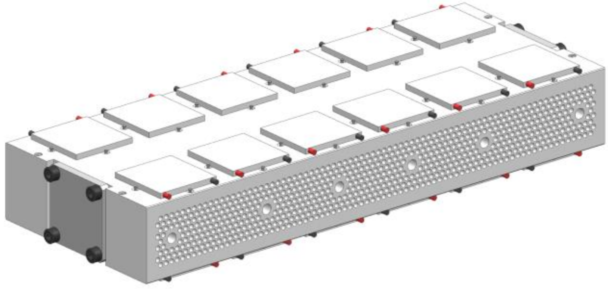


Figure 4. TCU primary block with TEDs, top and bottom.

On the outer surfaces of the TEDs are the control blocks, one of which has an integrated electrical box in the latest designs to improve the overall form of the design [see *Figure 5*]. These take a cooling medium, typically temperature-controlled water, and use it to remove any changes in temperature caused by the TEDs.

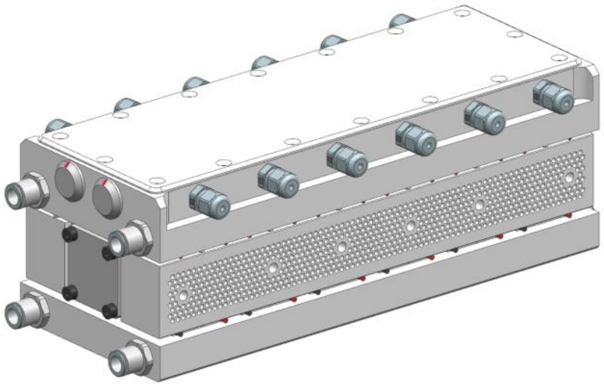


Figure 5. TCU primary block with TEDs and control blocks.

The remainder of the design is primarily around the inlet and outlet of the medium, as well as the internal mixing that occurs before the temperature probe that controls the unit as close to the TEDs as possible [see **Figure 6**]. A variety of inlet and outlet combinations can be used depending on what suits the target application best.

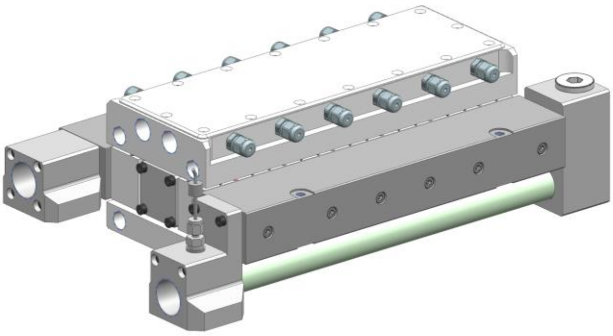


Figure 6. Example of fully built setup of TCU.

2.2. Scaling the TCU capabilities

The latest iterations of the TCUs have pushed the manufacturability, ease of assembly and size / weight of an individual unit to a point where larger is going to be too difficult to manufacture.

However, providing that the output of each unit is the target temperature within a certain range (usually ±0.01 °C or better), and all of the temperature probes are calibrated so that they are all outputting the same value as accurately as possible, then multiple units in parallel [see *Figure 7*] will combine in a way that the combined output will *still* be within the permitted range [see *Figure 8*]. In principle, this should equate to an averaging effect, but assuming worst case scenario, where no oil streams mix, any probe measurement will measure within specification.

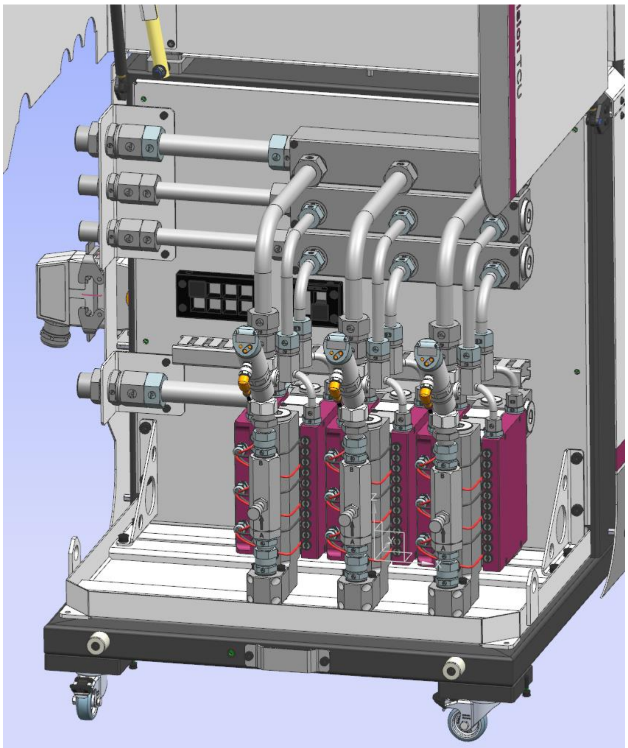


Figure 7. Example of multi-TCU parallel setup capable of 60 l/min

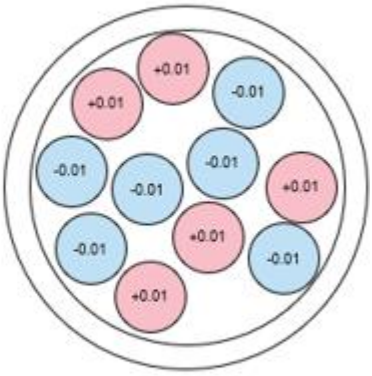


Figure 8. Example of worst-case multi-TCU combined output

3. Results and real machine examples

For most of the testing, a combination of the probe on the unit itself, and additional probes in other locations in the flow, as well as thermocouples at specific points around the circuit are used to measure and verify the test results. In most cases, the measurement devices are not calibrated to each other, because proving the *change* in temperature is much more important than the *absolute* temperature. As the investigations move to units truly in parallel, getting the probes calibrated to a master becomes much more critical.

The units have been in use on the Twin Turret Generator (TTG) family of machines for a number of years, controlling both oil and water circuits, continuously running.

The oil circuits for these machines are typically running VG5 to VG64 oils, and the graph [see *Figure 9*] shows two of them holding temperature to ±0.005 °C over a 30 minute period with a flow rate of 10 l/min through each unit.

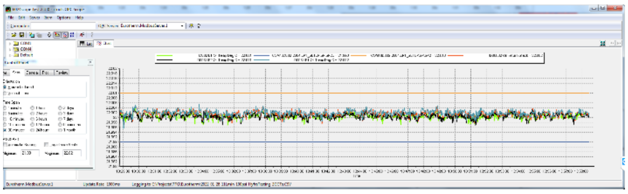


Figure 9. Two TCU outputs over 30 minutes, VG5 and VG 64 oils

The units have also been run with process coolant (oil emulsion) at flow rates of 22 l/min, and the graph [see *Figure 10*] shows that the unit was holding ±0.0065 °C for an hour.

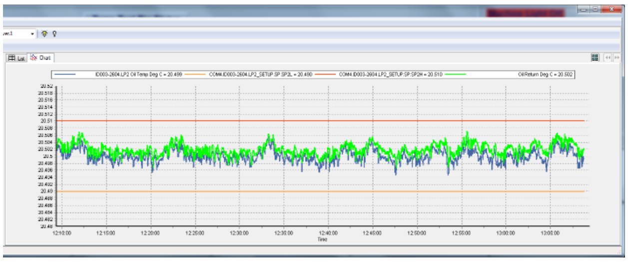


Figure 10. Single TCU output over 1 hour, with two probes, 22 l/min

The latest tests were done on an in-house grinding operation, on one of our most stable machines. The facility itself has a conditioned environment where the air is always held to ±0.1 °C. The chillers in the facility are all water-condensing, to minimise the thermal load.

When the customer optic [see **Figure 11**] was generated [see *Figure 12*], ripples could be seen on the optic [see **Figure 13**] which, although still well within specification, would have a large reduction in post-process polishing time if they could be removed.

After installing a TCU in the coolant line, controlling 20 l/min to a temperature of ±0.01 °C, the measured surface became sub-micron PV form error.

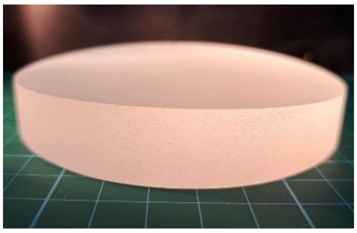


Figure 11. Customer optic.

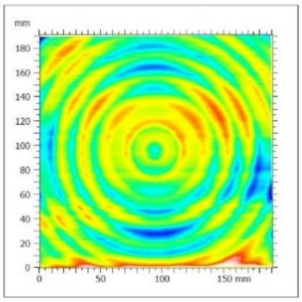


Figure 12. Measured surface with ≈ 3 µm PV form error

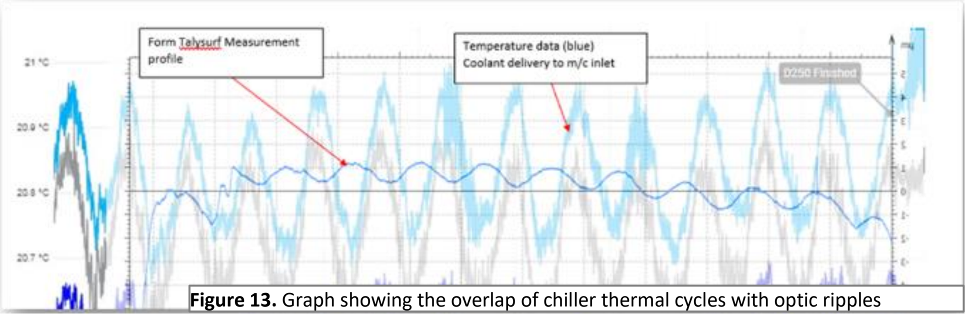


Figure 13. Graph showing the overlap of chiller thermal cycles with optic ripples

The units have also been tested at pressures of 100 bar, and left pressurised for several hours, with no loss of pressure or leakage. Primarily, this was due to an actual target of 70 bar, with a factor of safety of 1.3.

In a test done for a customer, the surface profile of a 250 mm plano optic showed ripples of ±0.5 µm, which could be overlayed almost perfectly with the cycling of the chiller connected to the system. Upon installation of TCUs in the process coolant feed, the ripples decreased to ±0.1 µm, which directly reduces the polishing requirements of following operations.

4. Summary

The units, with demanded flow rates of 5 to 10 l/min have been in operation on multiple TTG machines over numerous years and have had a clear benefit to the output quality of numerous components, frequently reducing post-grinding polishing operations on optical components by half or better.

As the requirements for utilising the units has tended to higher volumetric requirements of medium, larger and more optimised units have been designed, as well as the concept and proofing out of the parallel units.

Calculations around each unit can be done to determine approximate values for parameters such as time take for the medium to travel the hole length and the pressure drop across the holes [see **Figure *16Error! Reference source not found.*** and **Figure *14***].

Pressure drops are difficult to measure across the units due to the calculated, and measured, drop being almost negligible until the flow rates reach the highest flow rate limits of the units. Most of the measured drops tend to be in the fittings that get connected to the units to create the inlets and outlets.

5. Conclusion and future work

The TCUs are a customisable solution to many thermal issues, that can be applied to a broad range of fluidic mediums to achieve temperature controls exceeding ±0.05 °C, improving with the initial control of the supplied medium.

Utilised within spindles, they have helped minimise any change of position of tools. Utilised as part of a coolant delivery system that have prevented growth of both the tools and the components during long cycles that could otherwise remove the ability to control the manufacturing to the tight required tolerances.

The primary goal of evolving the TCUs is to maximise the flow rate capability within a single unit with minimal compromises to other variables, such as pressure drop and thermal inertia.

As the unit approaches a semi-optimum point, a much more in-depth study is required to quantify the capabilities of the unit for a variety of mediums, flow rates and other variables. This will allow graphs to be generated that would give end users a starting point to look up their specific mediums and determine what would be required to make a functioning system.

Another thing that has been important is stability of the incoming water, that controls the temperature of the outside plates [see **Figure 3**]. Although the stability is not absolutely critical, it can be seen that variations in these temperatures cause an imprinting effect onto the medium itself. One of the future tests will be to determine how beneficial it will be to have an additional TCU in the flow of the water, to stabilize that channel, where the output feeds all additional units, as well as its own cooling plate.

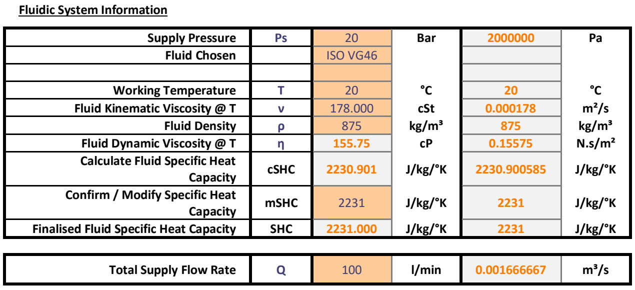
More work is also being done to investigate the effect of putting multiple units in series, with both the same, and different power levels of TCUs to investigate the effects of using the TCUs as their own version of the bulk thermal management.

Another important phase of the unit will be utilising 3D printing. Calculations and computations fluid dynamics (CFD) have both shown that narrow slot perpendicular to the faces that the TEDs sit on give lower pressure drops, higher surface area and minimised thermal inertia of the block, while making the manufacturing stages much simpler. There are other manufacturing methods, such as electrical discharge machining (EDM) and electrical chemical machining (ECM) which could both create the deep slots, but current investigation have shown that the costs would be prohibitive over deep hole drilling.

References

[1] Thermal issues in machine tools. Knapp, W et al, CIRP annals, Manufacturing Technology 61.pp771-791.2012

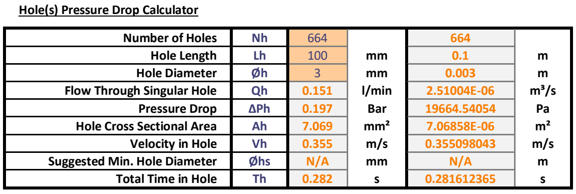
[2] Temperature Control in Machine Tools UK Patent GB 2591168 B, M Pierce, M Tucker, B Pike, 2019



Fluidic System Information

Supply Pressure	Ps	20	Bar	2000000	Pa
Fluid Chosen		ISO VG46			
Working Temperature	T	20	°C	20	°C
Fluid Kinematic Viscosity @ T	ν	178.000	cSt	0.000178	m²/s
Fluid Density	ρ	875	kg/m³	875	kg/m³
Fluid Dynamic Viscosity @ T	η	155.75	cP	0.15575	N.s/m²
Calculate Fluid Specific Heat Capacity	cSHC	2230.901	J/kg/°K	2230.900585	J/kg/°K
Confirm / Modify Specific Heat Capacity	mSHC	2231	J/kg/°K	2231	J/kg/°K
Finalised Fluid Specific Heat Capacity	SHC	2231.000	J/kg/°K	2231	J/kg/°K
Total Supply Flow Rate	Q	100	l/min	0.001666667	m³/s

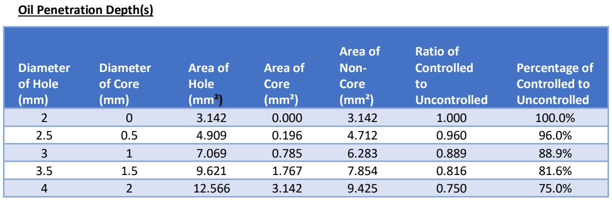
Figure 16. Example fluidics system information



Hole(s) Pressure Drop Calculator

Number of Holes	Nh	664		664	
Hole Length	Lh	100	mm	0.1	m
Hole Diameter	Øh	3	mm	0.003	m
Flow Through Singular Hole	Qh	0.151	l/min	2.51004E-06	m³/s
Pressure Drop	ΔPh	0.197	Bar	19664.54054	Pa
Hole Cross Sectional Area	Ah	7.069	mm²	7.06858E-06	m²
Velocity in Hole	Vh	0.355	m/s	0.355098043	m/s
Suggested Min. Hole Diameter	Øhs	N/A	mm	N/A	m
Total Time in Hole	Th	0.282	s	0.281612365	s

Figure 14. Example hole drop calculations



Oil Penetration Depth(s)

Diameter of Hole (mm)	Diameter of Core (mm)	Area of Hole (mm²)	Area of Core (mm²)	Area of Non-Core (mm²)	Ratio of Controlled to Uncontrolled	Percentage of Controlled to Uncontrolled
2	0	3.142	0.000	3.142	1.000	100.0%
2.5	0.5	4.909	0.196	4.712	0.960	96.0%
3	1	7.069	0.785	6.283	0.889	88.9%
3.5	1.5	9.621	1.767	7.854	0.816	81.6%
4	2	12.566	3.142	9.425	0.750	75.0%

Figure 15. Table showing thermal penetration percentages for various hole sizes