ISSN 1454 - 8003
Proceedings of 2016 International Conference on Hydraulics and Pneumatics - HERVEX
November 9-11, Baile Govora, Romania

INVESTIGATION OF FLUIDIC SYSTEMS IN MACHINE TOOLS

Linart SHABI[1], Juliane WEBER[2], Jürgen WEBER[3]

[1] TU Dresden, Institute of Fluid Power, shabi@ifd.mw.tu-dresden.de

[2] TU Dresden, Institute of Fluid Power, juweber@ifd.mw.tu-dresden.de

[3] TU Dresden, Institute of Fluid Power, mailbox@ifd.mw.tu-dresden.de

Abstract: *In the area of manufacturing technology, machine tools represent a significant part of machine equipment in a company. Besides productivity, the demands on the accuracy of components as well as on the energy efficiency of production processes rise. During the production process a part of the electrical energy is converted into thermal energy and thermo-elastic deformations occur. These deformations are influencing the position of the machine's tool centre point and lead to a reduced accuracy. Therefore, the fluidic systems are an essential element to control the thermo-elastic characteristics of machine tools.*

In the paper the behavior of the overall fluidic systems in a modern cutting machine tool is investigated, since these are absolutely necessary to provide an optimal thermal behavior and achieve highest accuracy. With new concepts of system structures fluidic system also offer a high potential to increase the energy efficiency of the machine.

The main targets of this paper are firstly, to identify and examine the existing fluidic systems of a machine tool. A performance measurement of the machine with defined load processes was carried out, to get information about the energy demand and distribution. Here is the focus on describing the cooling system because it is used to cool the motor spindle and its thermos-elastic deformations are directly influencing the TCP. Secondly, to develop a thermal model as a network model (lumped parameters) of the cooling system. Lastly, to derive basic information on the temperature characteristics of the cooling system and its sub-units in order to develop optimized structural concepts and control strategies for fluidic systems.

Keywords*: machine tools, heat transfer, cooling system, energy efficiency*

Nomenclature

A	m²	Area of pipe
Cp	J/(kg·K)	Specific heat capacity at constant pressure
D	m	Hydraulic diameter
d_i	m	Inner diameter
E	J	Energy
F	N	Force
i_1	A	Phase current
L	m	Length of tubes
$\dot{m}$	kg/s	Mass flow
Nu	-	Nusselt number
Re	-	Reynolds number
p	bar	Pressure

P_{el}	W	Electrical power
P_{hy}	W	Hydraulic power
$P_{th}, \dot{Q}$	W	Heat flow
P_{mech}	W	Mechanical power
Pr	-	Prandtl number
t	s	Time
u_{1N}	V	Phase voltage
$T_{E1}/\,T_{E2}$	°C	Inlet/ outlet temperature electrical cabinet
$T_{T1}/\,T_{T2}$	°C	Inlet/ outlet temperature rotary table
$T_{MS1}/\,T_{MS2}$	°C	Inlet/ outlet temperature main drive (spindle)
$Q_E\,/Q_T/\,Q_{MS}$	J	Thermal energy of electrical cabinet, rotary table and main drive
$\dot{V}$	m^3/s	Volume flow
v	m/s	Feed rate
α	$W/(m^2 \cdot K)$	Heat transfer coefficient
ΔT	°C	Temperature difference
λ_{Fluid}	$W/(m \cdot K)$	Thermal conductivity (water/Antifrogen® N mixture)
ν	m^2/s	Kinematic viscosity
ρ	kg/m^3	Density

1. Introduction

Over the last few years, energy saving has become a more and more important topic and the public awareness of environmental issues increased significantly. Using environmental friendly and energy efficient products, much energy and many raw materials could be saved. In recent times, the development in the industrial sector is strongly focused on producing in a more energy-efficient way. Depending on the company, machine tools require up to 68 % of the companies' total energy demand [1].

With machine tools, various production processes such as drilling, cutting, milling, etc. can be realized. During these production processes, a large amount of electrical or mechanical energy is converted into thermal energy. The generated heat from the production process and from the drives dissipates and the warmed-up parts or components need to be cooled accordingly. Otherwise thermo-elastic deformations occur that at the end are influencing the position of the tool center point (TCP) of the machine tool. This has to be avoided in order to guarantee a precise production.

The main targets of this paper are firstly, to identify and examine the existing fluidic systems of a machine tool. Secondly, to develop a thermo-hydraulic network model (lumped parameters) of the cooling system. This cooling system is used to cool the main drive (motor spindle), which was identified as the main heat source inside the machine tool. Lastly, to provide basic statements on the temperature characteristics of the cooling system and its sub-units.

Figure 1 illustrates the methodology of the investigations. It is divided into four mutually dependent steps: In the first step, a demonstration machine with its main fluidic system is defined. Secondly, the measurement of the machine is carried out with a defined test cycle. With the help of the machine data as well as the circuit diagrams a system structure of the fluidic systems is derived. In the last step, the initial parameters of the measurement are included in the model and it is validated against the measured data. With this model one is able to examine and evaluate new concepts for the cooling system.

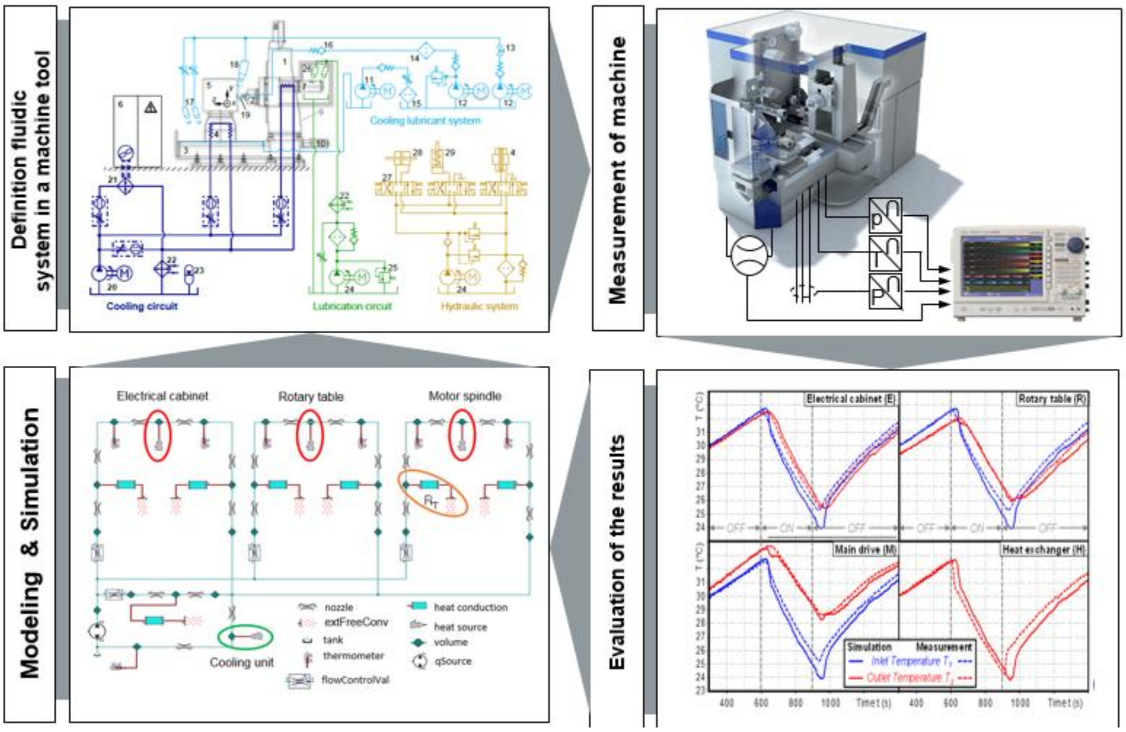
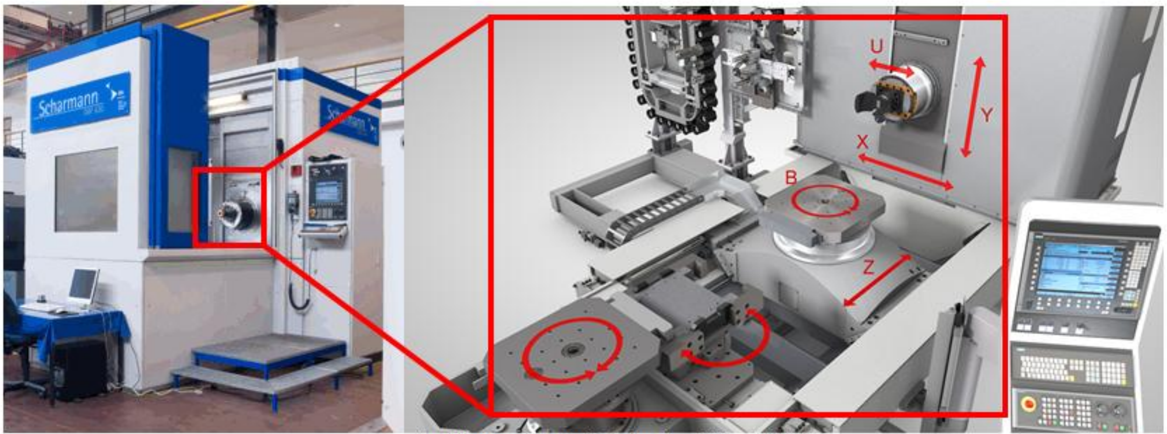


Fig. 1. Methodology of investigation of a demonstration machine

2. Demonstration machine and its fluidic tempering systems

In the first step, a machine was chosen for the experimental investigation as a demonstration machine (Figure 2). The selected and analyzed machine, type “Scharmann DBF630”, has five axes (X, Y, Z, U and B) and a driving power of 35 kW. The speed of the main drive ranges from 1 to 3500 min^{-1}, the working area of X-, Y-, and Z-axes amounts to (850 x 700 x 800) mm.

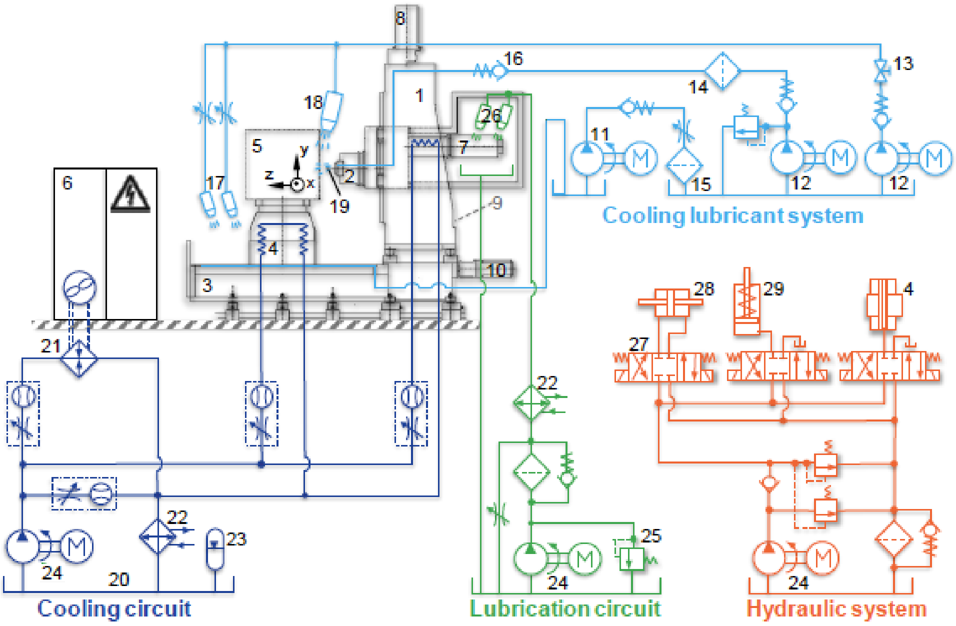


https://www.starrag.com/de-de/machine-364?machineld=53

Fig. 2. Demonstration machine DBF 630

The fluidic systems are an essential element to control the thermo-elastic characteristics of machine tools. They undertake a number of tasks such as tempering, lubrication, flushing and clamping. The fluidic systems represent an essential part of the total electric energy consumption and are also an important heat source.

The demonstration machine DBF630 consists of four main fluidic systems: Cooling system, cooling lubricant system, lubrication system and hydraulic system, see Figure 3. As previously mentioned, the focus is to examine the fluidic systems and describe the cooling system and its sub-units. The cooling medium of the cooling system consists of a mixture of water and Antifrogen® N (60% H_2O). The main function of the cooling lubricant, the lubrication and the cooling system is the heat dissipation from the production process, the mechanical parts (friction losses) and the drives (motor losses).



1	Column
2	Headstock
3	Bed
4	Rotary table
5	Workpiece
6	Electrical cabinet
7	Main drive
8	Y axis drive (spindle)
9	X axis drive (spindle)
10	Z axis drive (table)
11	Centrifugal pump
12	Submersible pump
13	Shutoff valve
14	In-line filter
15	Belt filter
16	Check valve
17	Nozzles for flushing
18	Nozzle for external coolant supply
19	Internal coolant supply (through the tool)
20	Tank
21	Air-cooling cabinet
22	Coolant device
23	Accumulator
24	Fixed displacement pump
25	Pressure relief valves
26	Nozzles (cooling headstock, lubrication (e.g. main drive)
27	Directional control valves
28	Tool (clamping/release)
29	Break (at standstill)

Fig. 3. Main fluidic systems of DBF 630 [2]

Cooling system

The cooling system consists of three sub-units, electrical cabinet (6), rotary table (4) and main drive (7). A fixed displacement pump (24) supplies the cooling medium and the coolant device (22) cools down the heated fluid to a set temperature. The heat generated by conversion of electrical energy into mechanical and hydraulic energy can be transmitted by means of the fluid to the heat sink cooling unit (22).

Cooling lubricant system

The main functions of the cooling lubricant system are on the one hand, the cooling of the tool and the workpiece during a manufacturing process and on the other, the removal of the originating metal chips during production. Here, two submersible pumps (12) are responsible for the coolant supply to the processing zone. One high pressure pump is used for the internal coolant supply through the tool (19), another low pressure pump ensures the flushing of the processing zone (17) and the external coolant supply (18). The centrifugal pump (11) transports the contaminated fluid from a dirt coolant tank through a belt filter (15) back to the cooling lubricant tank.

Lubrication system

The primary function of the lubrication system is the lubrication of the mechanical parts within the main drive (7) to reduce friction and friction losses. Here, the pump (24) delivers the lubricant through the filter and cooling unit (22) to the nozzles (26). The lubricant is distributed between the moving parts and the emitted fluid is retained and led back to the tank.

Hydraulic system

The hydraulic system is used for clamping the tool (28) or the rotary table (4). Two pressure relief valves are integrated behind the fixed displacement pump (24) and limit the pump pressure in a range of 120 bar and 160 bar.

3. Experimental investigation

After the definition of the main fluidic systems in the machine tool was successfully completed, experimental investigation follows. For this second step within the methodology of investigation (see Figure 1), measurements were performed on each system of the demonstration machine (Figure 4a). Also, a performance measurement of the overall machine tool was carried out. To warm up the machine in idle operation mode a load regime was applied. Therefore, two different test cycles are used for the investigations: Test cycle 1 (short 275 s), to examine the energy demand of the overall machine (see figure 4b) and test cycle 2 (long 1400 s) to investigate the temperature behavior of the sub-units. In general, the performance measurement of the machine tool is divided into different sub-processes, such as: switching machine on and off, warm-up phase, set-up operation, emergency stop, idle operation and production process [3]. Here in this paper, four phases are chosen:

- Warm-up with starting up the machine until thermal equilibrium is achieved within the fluidic systems
- Set-up operation with exchange between workpiece and tool
- No-load phase, individual movements of axes and spindle (Figure 4b)
- Manufacturing process

All results shown in this paper refer to the test cycle 1 (depicted in Figure 4b) and test cycle 2. Firstly, the spindle accelerates several times to its maximum speed at 3500 min^{-1} and decelerates again. This is followed by the movement of the linear axes X, Y, and Z. The energy consumption for the test cycle 1 (275 s) is illustrated in Figure 4c. The energy amounts are calculated from the measured electrical power values of the whole machine and of each subsystem. The following equations are used to determine the distribution of the total energy consumption:

$$P_{el} = \overline{P_{\Sigma}(t)} \tag{1}$$

$$P_{\Sigma}(t) = u_{1N}\, i_1 + u_{2N}\, i_2 + u_{3N}\, i_3 \tag{2}$$

$$P_{th} = \dot{Q} = \dot{m}\, C_p \Delta T \tag{3}$$

$$P_{hy} = p\, \dot{V} \tag{4}$$

$$P_{mec\,h} = Fv \tag{5}$$

$$E = \int_{t1}^{t2} P\, dt \tag{6}$$

The largest share of consumed energy of about 45 % is used to drive the axes. Furthermore, the fluidic systems require 44 % of the total energy consumption. The remaining 11 % are needed by the auxiliary equipment, such as lighting, CNC control and pneumatic systems. Concerning the fluidic systems the cooling lubricant system has the highest energy consumption with approximately 16 % of the total energy consumption of the machine tool. The cooling system and lubrication system each use about 12 % of the total energy, and the smallest portion of energy consumption of 4 % is caused by the hydraulic system.

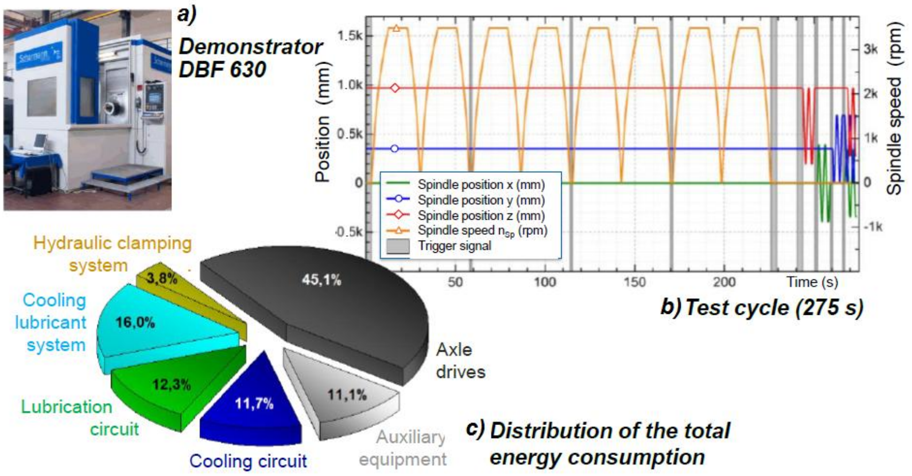


Fig. 4. Distribution of energy consumption of DBF630 in no-load test cycle 1 [4]

As mentioned, the motor spindle was identified as the main heat source in the machine, so the energy distribution in the cooling system has been examined in further detail. Therefore, additional temperature sensors (thermocouples type T class 1) and flow sensors were installed. Figure 5 shows the position of the measuring points as well as the temperature characteristics for the test cycle 2 [5].

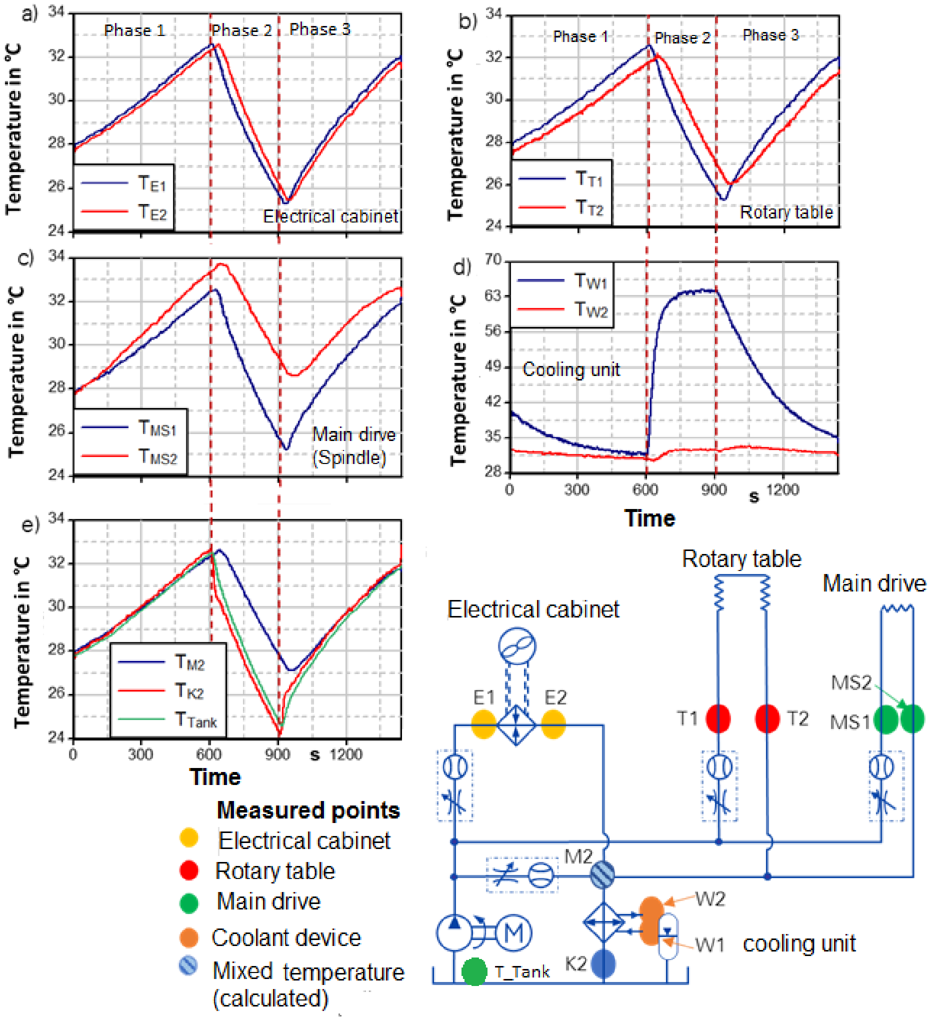
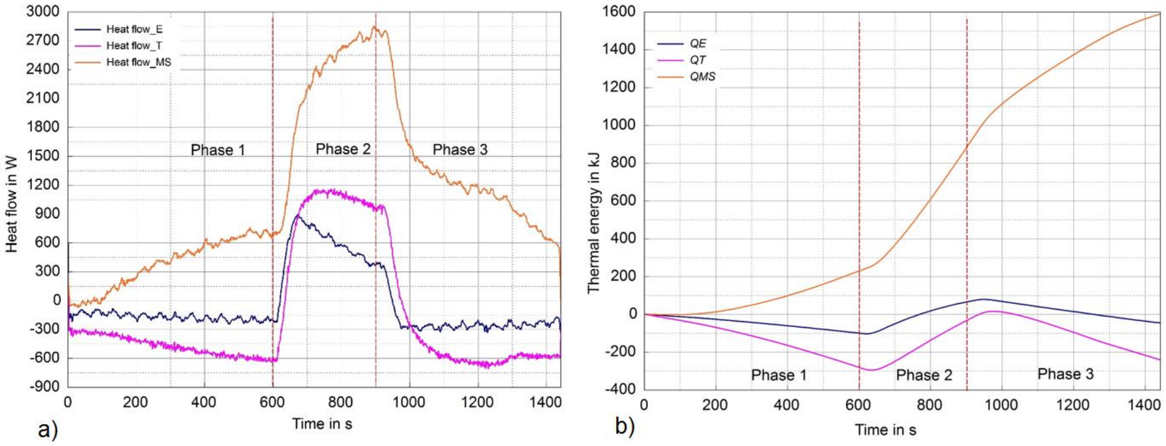


Fig. 5. Temperature characteristics at different positions within the cooling system

Due to the two-point control of the cooling unit all temperature profiles can be divided into three phases: in phase 1 and 3 the cooling unit is off, while in phase 2 it is activated. The temperature development in the electrical cabinet and the rotary table clearly differs from that in the motor spindle. At the electrical cabinet and the rotary table, the temperature difference between the outlet (T_{E2} /T_{T2}) and the inlet (T_{E1} /T_{T1}) is about -0.75 °C, so the cooling medium is cooled while the components are warmed up. This phenomenon contradicts the real function of a cooling medium in a cooling system. Only the main drive is cooled actively during all phases. Here, the outlet temperature of the cooling medium T_{MS2} is higher ($\Delta T = 1,5^{\circ}C$) than the inlet temperature T_{MS1}.
The functional principle of the cooling unit is similar to refrigerator and will not be explained further. The used coolant in the cooling unit is R134a. With the aid of the measured temperatures and volume flow rates the heat flow and the thermal energy of the electrical cabinet, the rotary table and the main drive (spindle) are calculated from equation (3 & 6) . Figure 6a and 6b show the heat flow and the thermal energy for the electrical cabinet, the rotary table and the main drive (spindle) of the cooling system.



c)

	Q_E in kJ	Q_T in kJ	Q_{MS} in kJ
Phase 1	-99	-280	230
Phase 2	165	248	656
Phase 3	-101	-183	651

Fig. 6. Heat flow & thermal energy in the cooling system calculated from the measured temperature values

In phase 1 and 3 the generated heat of the spindle is dissipated by the cooling medium, the amount of the thermal energy is in phase 1 (230 kJ) and in phase 3 (651 kJ). However, the electrical cabinet and the rotary table are heated by the cooling medium, here is the amount of the thermal energy in phase 1 and 3 ΔQ_E (-99 kJ, -101 kJ) and ΔQ_T (-280 kJ, -183 kJ), see Figure 6c. A clear difference is recognized when the cooling unit is switched on in phase 2 between $t_{on} = 600\,s$ and $t_{off} = 900\,s$. When the cooling liquid is actively cooled, the heat flow increases and all three components transfer thermal energy to the cooling system and are cooled.

4. Model design for the simulation

4.1. Model structure and validation of the simulation result

Based on the first and second steps of the methodology (presented in Figure 1), a thermo-hydraulic model is developed with the help of the machine documentation and hydraulic plans of the demonstration machine. Figure 7 shows the model structure of the cooling system, which was implemented in the simulation. The cooling system consists mainly of a pump, flow control valves, hydraulic pipes and a cooling unit. In the simulation each hydraulic pipe is modelled by a hydraulic volume and a hydraulic resistance. The geometrical parameters (length, inner and outer diameter) of the pipes are directly taken from the machine documentation. Moreover, the heat transfer between the pipes and the environment is taken into account. The following equation is used to define the heat transfer coefficient:

$$\alpha = \frac{Nu \cdot \lambda_{Fluid}}{L} \tag{7}$$

With the aid of the flow rate, the kinematic viscosity and the inner diameter of the hydraulic pipes the Reynolds and the Prandtl number are calculated. Depending on the pipes' size in the demonstration machine the Reynolds number is about 4000 [6] and therefore, all further calculations can be done for a turbulent flow.

$$Re = \frac{\dot{V} \cdot D}{A \cdot \gamma} \tag{8}$$

$$Pr = \frac{C_P \cdot \rho \cdot \gamma}{\lambda} \tag{9}$$

$$Nu = 0{,}0235(Re^{0{,}8} - 230)\left[1 + \left(\frac{d_i}{L}\right)^{\frac{2}{3}}\right](1{,}8Pr^{0{,}3} - 0{,}8) \tag{10}$$

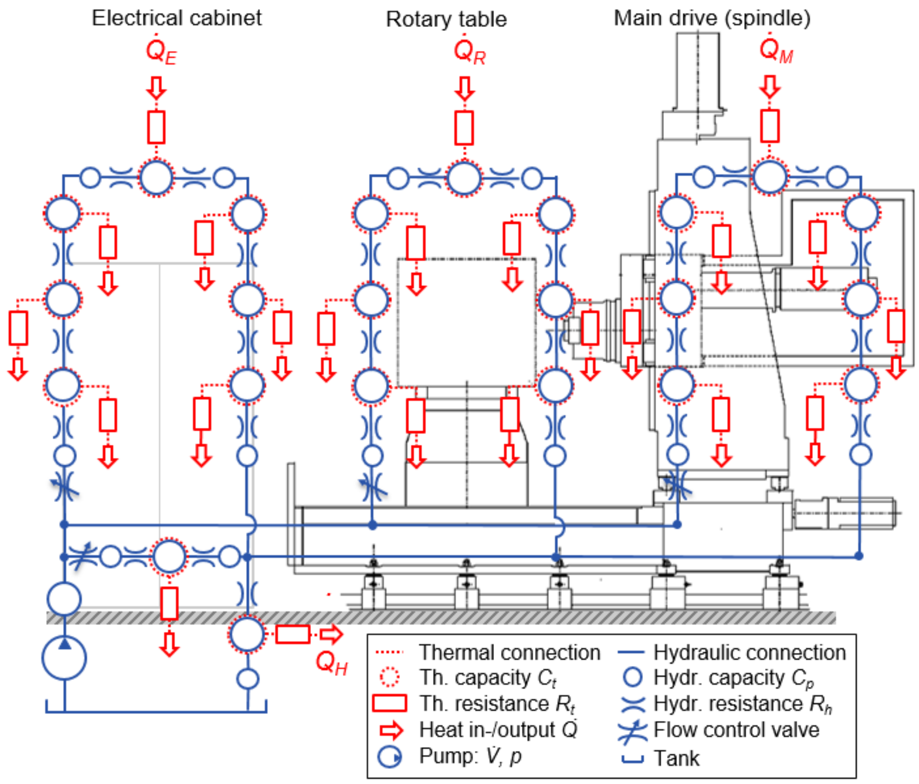


Fig. 7. Model structure of the cooling system

From the developed model the following temperature profiles for the electrical cabinet, the rotary table and the main drive were calculated. The red lines in Figure 8 show the temperature development of the simulation and the blue ones of the measurement. T_{E1}, T_{T1} as well as T_{MS1} are the input temperatures; T_{E2}, T_{T2} and T_{MS2} are the outlet temperatures of the electrical cabinet, the rotary table and the main spindle, respectively. The temperature development of the simulation is nearly identical to the temperature development of the measurement. The modeled system and the considered structure in the simulation model behaves in the same way as the real machine.

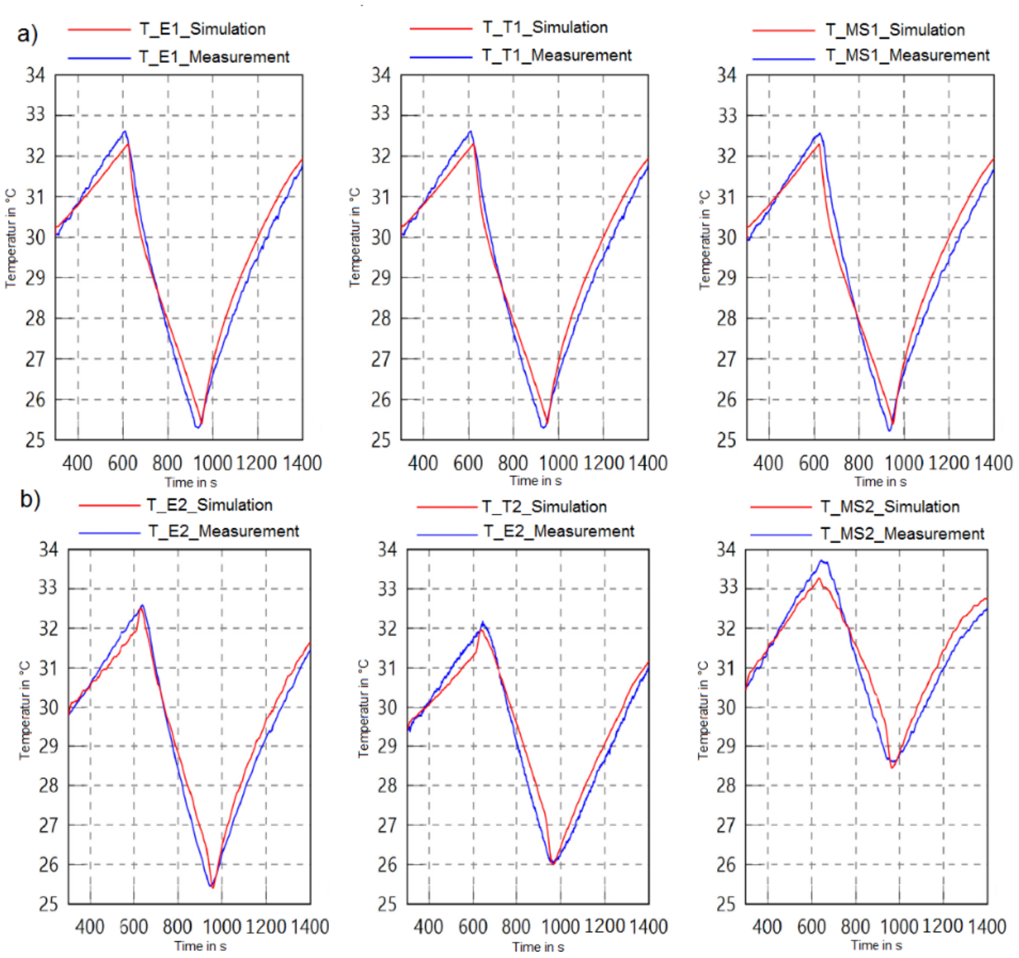


Fig. 8. Comparison of temperature development, simulation and measurement,
a) inlet temperatures, b) outlet temperatures

4.2. Simulation-based optimization of cooling system

The work in this part focuses on further development of the complete structure of the fluidic tempering systems. The distribution of energy consumption shows, that the energy demand of fluidic systems is about 44 % of the total energy consumption in the machine tool. There is major potential to improve the function of the fluidic systems. Furthermore, the investigation of the DBF630 depicts that sufficient cooling capacity exists but, however, the cooling is insufficiently adjusted to the process and to the individual demand of the machine components. In order to address this deficit, it is necessary to think about new concepts and new structures of fluidic systems.

At this point, two different strategies can be derived. On the one hand the system structure can be decentralized (see Figure 9), which can be very helpful in the case of the cooling system. The decentralization allows an adequate supply and, thus, an appropriate temperature control of each individual component. A similar approach (decentralization of system) is taken in the domain of electrical engineering, for example by using more flexible and smaller electrical cabinets and power supplies. So the components of the machine can be controlled individually [7].

On the other hand the system structure can be centralized. For example by centralization of supply units by using one hydraulic pump for both, the parallel pressure build-up in the cooling lubricant system and in the lubrication system. So this method has a large potential to minimize the energy demand of the machine tool and, therefore, to reduce the heat introduced into the machine because of energy losses. These two different approaches are investigated in order to find the best solution. It is expected, that a combination of both approaches delivers the best solution regarding the lowest power demand and power losses in the fluidic systems.

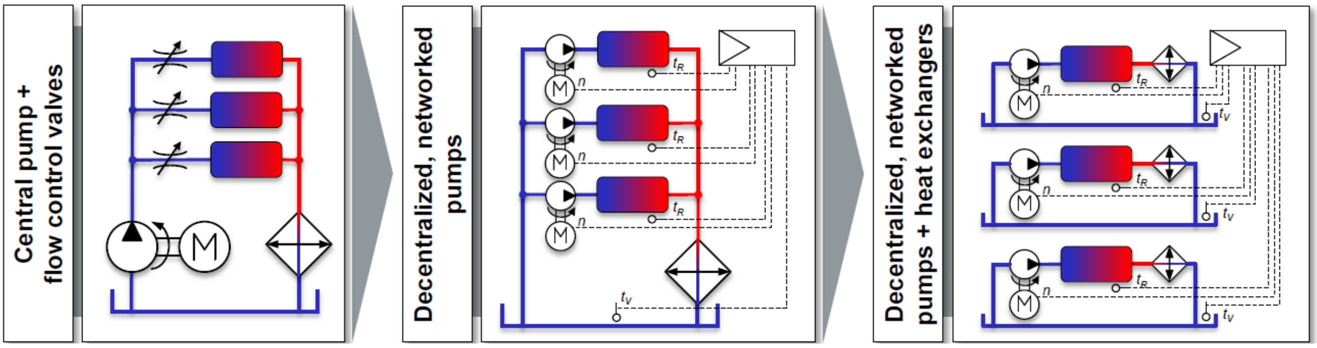


Fig. 9. New concepts of decentralization for adequate supplies of various consumers [8]

5. Summary

In conclusion, three major results were described in this paper. Firstly, with the help of the experimental investigation, new knowledge about the thermal behavior as well as the distribution of energy consumption of the demonstration machine and in particular of the cooling system was gained.
Secondly, using the existing machine documentation and circuit diagrams, a system structure of the cooling system was derived. The developed network model (lumped parameters) was implemented and parameterized in the simulation. Afterwards the simulation model was successfully validated against the measured temperature profiles.
Thirdly, the simulation model was used to develop optimized concepts for the fluidic systems. Further considerations are on the one hand to test the existing network model at different operating modes, e. g. a production process, and on the other hand the test of new concepts for adequate supplies of various consumers with the aim of ensuring a uniform temperature distribution within the machine tool at minimal energy consumption.

Acknowledgements

The presented research activities are part of the project “Thermo-energetic description of fluid systems” (Ref. No. CRC/TR 96, A04). The authors would like to thank the German Research Foundation (DFG) for the financial support.
Funded by
DFG Deutsche Forschungsgemeinschaft

References

[1] F. Lubnau, ”Mehr Transparenz im Unternehmen durch effizientes Energemanagment und Condition Monitoring”, Hannover Messe 2011;
[2] K. Großmann, O. Gritt, “Thermo-energetic Design of Machine Tools“, Heidelberg: Springer Berlin Heidelberg, 2014, S. 52;
[3] A. Dietmair, A. Verl, M. Wosnik, “Zustandsbasierte Energieverbrauchsprofile“, wt Werkstattstechnik online, ISSE-2008, Jahrgang 98 2008;
[4] J. Weber, H. Lohse, J. Weber, “Thermo-energetic Analysis of the Fluid System in Cutting Machine Tools“, 10IFK in Dresden 2016;
[5] S. Pursian, “Thermo-energetische Modellierung der Fluidsysteme eines Bearbeitungszentrums“, Diploma thesis, TU Dresden 2015;
[6] D. Will, N. Gebhardt, H. Ströhl, (Hrsg.), “Hydraulik-Grundlagen, Komponenten, Schaltungen“, 5 Aufl., Springer-Verlag Berlin Heidelberg 2011;
[7] C. Plattmann, “Anlagen dezentral absichern“, ISSE-2015, Journal Chemie Technik June 2015;
[8] J. Weber, J. Weber, “Thermo-energetische Beschreibung fluidtechnischer Systeme (Thermo-fluidtechnik)“ Sub-Project A04/ TR96 2015.