Topology optimization of fluid cooling systems for machine tools

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Abstract.

Fluid cooling systems for machine tools commonly operate with a constant speed drive pump and manual valves. The volume flow rate for cooling the components is set to a fixed value during commissioning and is not changed by the user during operation. Recent research proposes temperature control for machine tools. This requires variable speed drive pumps or proportional valves. A major obstacle to implementing such a system are material costs. This paper presents a method for designing such a system with minimal costs.

Keywords. optimization, machine tools, cooling systems, compensation, variable speed pumps, simulation, temperature (field), cost

1. INTRODUCTION

Usage of machine tools is indispensable especially for cutting, drilling and grinding. Therefore, they are widely spread in machine parks. In recent years' industry requests high quality production and higher productivity. Machine tools can meet the high demands, but during operation, heat is introduced to the machine tool. [1] mentions, that 75% of all geometric errors of machined workpieces can be attributed back to temperature variation of the machine.

Main heat sources in machine tools are spindles, linear drives, bearings and auxiliary units. Preventing the heat from spreading inside the machine tool, cooling circuits are installed. They absorb the heat near the source or prevent critical parts from varying temperature. When investigating the power,consumption of cooling and cooling lubricant systems, it is,observable that these systems consume about 45% of the overall electrical energy [2]–[4].

Various approaches to reducing energy consumption are being discussed in the scientific community. In projects such as EWOTek [2] optimization of components and load-dependent strategies for drives or the cooling unit are carried out. NCplus [3] investigates control strategies for the cooling unit besides other components and the NC control strategies.

Further approaches discuss load-dependent volume flow rate control for cooling channels in the machine tool. Kung-Ying Li et al. [5] focuses on the load-dependent supply of the main spindle. They investigate the deformation of the spindle depending on the temperature difference of the cooling fluid, the spindle and the state of the cooling aggregate. In [6] different structures of the cooling system are shown. Here, each cooling circuit in the machine tool is controlled regarding the amount of coolant provided. This control strategy is enabled with variable speed drive pumps and/or proportional valves. In the system topology proposed by [6] each cooling circuit has its own actuator. For complex machine tools e. g. DMU 80 eVo by DMG, this leads to a large number of pumps or valves.

For installing a load-dependent cooling system with varying cooling fluid supply and low installation costs, it is necessary to identify cooling circuits that can be supplied by the same actuator. For this task, optimization algorithms are useful tools. In case of the topology of the cooling system a mixed-integer non-linear problem has to be solved. Related work can be found in [7], [8]. These works describe the optimization of the water distribution system of multi-storey buildings that need to be supplied with fresh water. This involves the use of different kind of pumps to optimize the overall costs.

2. SYSTEM DESCRIPTION

In this section the tempering system used for cooling the machine tool frame is described. First the system design and afterwards the physical behavior of the components are described.

2.1. Cooling system for a machine tool frame

Aim of the test rig is the evaluation of load dependent cooling structures. The system design of the tempering unit can be seen in Fig. 1. The tempering unit consists of ten centrifugal variable speed drive pumps (Wilo-Yonos PICOSTG 15/1-13-180) commonly used in heating systems of buildings. They generate the volume flow rate through each circuit. Sensors measure the physical quantities volume flow rate, pressure and temperature. They can be used to evaluate the state of the tempering unit. Seven of the ten fluid circuits pass through a machine tool frame in order to temper it. The other three circuits are bypasses and are only used to change the temperature of the fluid without passing it through the machine tool frame. The fluid temperature can be controlled with two different units. The first is a liquid-air cooling system called FLKS 5 EC from Hydac. The system is driven by a fan that passes air through a heat exchanger and cools the fluid to ambient temperature. The heat transfer capacity can be controlled by the speed of the fan. The 2nd system is a instantaneous water heater with a connected load of 2kW. It allows to raise the temperature of the fluid up to 35 ◦C. The fluid used is water-glycol with a ratio of 70% to 30%.

The machine tool frame used at the test rig is built by Framag Industrieanlagenbau GmbH. It consits of a steel hull that is poured with Hydropol. Hydropol is a special filling material designed to have better damping behavior than conventional mineral cast. For temperature monitoring, 30 PT100-sensors are integrated. Seven fluid circuits are installed inside of the machine tool frame to control the temperature. There are three types of fluid circuits: The circuit located on the floor is the longest, it has a length of 18 965mm. It is installed as a spiral, where flow and return running in parallel. The task of this fluid circuit is to thermally decouple the machine tool frame from the cold foundation. The two fluid circuits, called guiding have a length of 3656mm. Their function is to dissipate heat introduced by hot chips

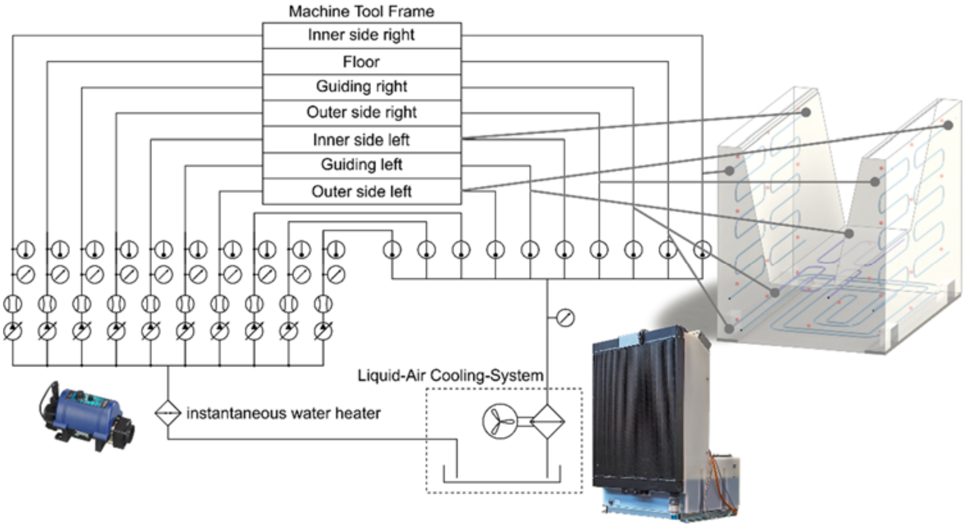

Figure 1. System design of the tempering unit

from the machine tool frame. For this purpose, the fluid circuits are placed in a meander under the collecting area. The remaining four fluid circuits have a length of 7105mm each

and are located in the sides of the machine tool frame. Their purpose is to minimize effects of environmental conditions such as solar radiation or changes in ambient temperature. Because of the usage of the machine tool frame as a demonstrator without production purpose, artificial heat sources are installed. In the area of the guiding, 20 heat mats with a power of up to 45W each are used. Second, there is an infrared light with a power of 1kW.

2.2. Mathematical description

A mathematical description of the system is given in the following section. It forms the basis for the optimization problem shown in section III.

To describe the heat flow $\dot{Q}$ dissipated from the machine tool the following equation can be used

$$\dot{Q} = \dot{V} \cdot c_p \cdot \rho \cdot (T_{\text{return}} - T_{\text{flow}}). \tag{1}$$

The volume flow rate $\dot{V}$ is measured with the integrated sensors. The specific heat capacity $c_p = 3849\ \text{J/kgK}$ and the density $\rho = 1044\ \text{kg/m}^3$ are material dependent properties. Both quantities are assumed to be temperature independent in the investigated range. The temperature difference $(T_{\text{return}} - T_{\text{flow}})$ between return and flow can also be measured with the installed sensors. The heat flow introduced by pressure losses is neglected. In addition to the heat flow transported by the tempering system, volume flow rate and pressure are important quantities because they determine the power consumption of the pumps. Calculating the pressure losses Δp depends on the volume flow rate $\dot{V}$ of the cooling circuit and the hydraulic resistance R

$$\Delta p = R \cdot \dot{V}^2. \tag{2}$$

The resistance R of each fluid circuit is calculated from measurements and given in Table 1. With pressure losses and volume flow rate of each circuit it is possible to interpolate the necessary rotational speed of the pump, with the given diagram 2. A second diagram helps to calculate the power consumption of each pump.

Table 1: Hydraulic resistances of fluid circuits

Name	**Hydraulic Resistance in $\frac{\mathbf{kg}}{\mathbf{m^7}}$**
R_1	$9.6 \cdot 10^{11}$
R_2	$1.59 \cdot 10^{12}$
R_3	$6.9 \cdot 10^{11}$
R_4	$9.8 \cdot 10^{11}$
R_5	$8.9 \cdot 10^{11}$
R_6	$5.2 \cdot 10^{11}$
R_7	$1.05 \cdot 10^{12}$
R_8	$4.7 \cdot 10^{11}$

3. OPTIMIZATION MODEL

The optimization problem has to scenarios for that it is solved. The two scenarios chosen in this problem describe he active times of the heating elements during one day: The heating mats are active from 6:30 am till 9:00 pm. In addition, the infrared light is active from 12:00 pm till 3:00 pm. Scenario 1 lasts from 6:30 am to 12:00 pm and 3:00 pm to 9:00 pm. In total the duration of scenario 1 is 11.5 h. Scenario 2 lasts from 12:00 pm to 3:00 pm, with heating mats and infrared light active, and lasts 3.0 h. The loads are based on a two shift system. For implementing the optimization problem, a set of constant parameters will be used.

C_{elec}	Electricity price 0.19 $€/kWh$
P_i	Set of pumps $i \in \{1,2,3,4,5,6,7\}$
T_S	Temporal share of scenario $S \in \{1,2\}$
d	Work days per year $d = 250$ d
y	Number of years $y = 5$ years
S	Set of scenarios
C_{acq}	Acquisition costs per pump 250 €
R_j	Hydraulic Resistance of each fluid circuit

Besides these constant parameters, there are also two types of variables. First, those that are controlled by the solver of the optimization problem, and second, variables that contain physical quantities.

$x_i = \{0,1\}$	If pump i is used $x_i = 1$ otherwise $x_i = 0$
$x_{i,j} = \{0,1\}$	If pump I is connected to fluid circuit j $x_{i,j} = 1$ otherwise $x_{i,j} = 0$
$n_{i,S} \geq 0$	Rotational speed of pump i
$\dot{Q}_{cool\ j,S} \geq 0$	Necessary heat flow for fluid circuit j during scenario S
$P_{elec\ i,S} \geq 0$	Necessary electrical power of pump I during scenario S
$\dot{V}_{i,S} \geq 0$	Volume flow rate of pump I during scenario S
$p_{i,S} \geq 0$	Pressure head of pump I during scenario S
$R_i \geq 0$	Hydraulic resistance seen from pump i

3.1. *Cost function*

For solving the optimization problem, a cost function has to be implemented. The solver tries to minimize the cost function. For our problem the cost function is

$$\mathrm{C} = \sum_{i=1}^{7} (x_i \cdot C_{\mathrm{acq}}) + \sum_{S=1}^{2} \sum_{i=1}^{7} \left(P_{\mathrm{elec}\, i,S} \cdot T_S\right) \cdot d \cdot y \cdot C_{\mathrm{elec}}. \tag{3}$$

and returns a value in €. Equation (3) can be separated into two parts. The first part describes the acquisition costs for all necessary pumps. The second part gives the cost that occur during operation for y years. Here the energy consumption is for each scenario is calculated and multiplied with energy costs C_{elec}.

3.2. *Constraints*

Constraints describe the suitable range where the solver searches for a solution. They are designed specifically and need to be adapted for other topologies. In the following, some constraints are listed that describe the structural design of the fluid system:

$$\sum_{i=1}^{7} \mathrm{x_i} \leq 7 \tag{4}$$

$$\mathrm{x_{i,j}} \leq x_i \qquad \forall i \in \{1, \dots, 7\}, j \in \{1, \dots, 7\} \tag{5}$$

$$\sum_{i=1}^{7} x_{i,j} = 1 \qquad \forall j \in \{1, \dots, 7\} \tag{6}$$

$$\sum_{i=1}^{7} \sum_{j=1}^{7} \mathrm{x_{i,j}} = 7 \tag{7}$$

$$\mathrm{x_i} \leq \sum_{j=1}^{7} x_{i,J} \qquad \forall i \in \{1, \dots, 7\}. \tag{8}$$

The meaning of (4) is that in the optimal topology no more than seven pumps are used. Equation (5)ensures that the connection between pump i and fluid circuit j is active only when pump i is purchased. Otherwise, the connection must be inactive. Equation (6) defines that each fluid circuit is supplied by exactly one pump. In (7), the behavior is implemented that there are exactly seven connections between pumps and fluid circuits. To ensure that each pump supplies at least one fluid circuit, (8) is used. Besides these structural design constraints, it is necessary to develop some constraints that help to model the physical behavior of the system. It is necessary to calculate the electrical power of the pumps, which is needed for the cost function (3). To calculate the electrical power, pressure and volume flow rate must be known. The necessary volume flow rate for each fluid circuit is obtained by (1). Here, two assumptions are made. First, the temperature difference ($T_{\mathrm{return}} - T_{\mathrm{flow}}$) is constant at 0.4 K. This assumption is based on measurements performed at the test rig. The second assumption is a constant heat flow that is transported out of the machine tool frame by each fluid circuit. The heat flow is given in Table. 2.

Table 2: Heat Flow in W transferred out of the machine tool frame when heating elements are active

Fluid circuit	**Heating mat active**	**Infrared light active**
Inner side right	20	400
Floor	20	0
Guiding right	250	20
Outer side right	20	80
Inner side left	20	400
Guiding left	250	20
Outer side left	20	80

The rearranged equation (1) using the defined variables above gives the total volume flow rate that pump i must deliver during scenario S

$$\dot{V}_{i,S} = \frac{1}{c_p \cdot \rho \cdot (T_{\text{return}} - T_{\text{flow}})} \sum_{j=1}^{7} \dot{Q}_{\text{cool}\ j,S} \cdot x_{i,j}. \tag{9}$$

With the volume flow rate known, the pressure head $p_{i,S}$ of each pump can be calculated with help of (2). The hydraulic resistance R_i is the parallel circuit connected to pump i. It is calculated through:

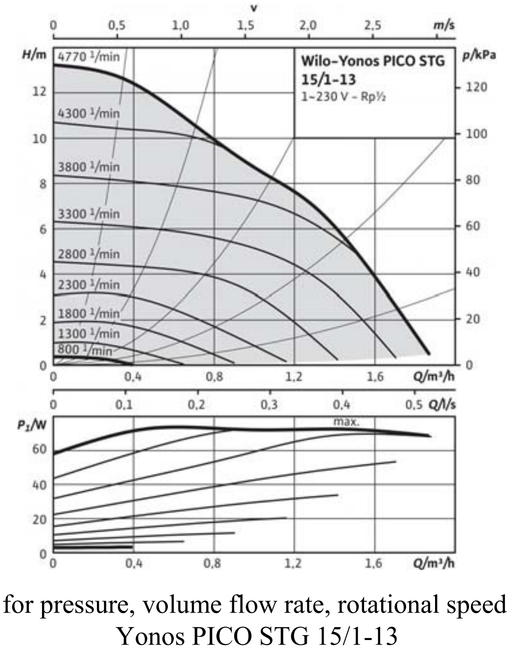

Figure 2: Diagram for pressure, volume flow rate, rotational speed and power of WIlo Yonos PICO STG 15/1-13

$$\frac{1}{\sqrt{R_i}} = \sum_{j=1}^{7} \frac{1}{\sqrt{R_i}} \cdot x_{i,j}. \tag{10}$$

The pressure head is now given by

$$\mathrm{p_{i,S}} = R_i \cdot \dot{V}_{i,S} + R_8 \cdot \sum_{i=1}^{7} \dot{V}_{i,S} \cdot x_i. \tag{11}$$

The first part of (11) represents the pressure loss of the parallel circuit supplied by pump i. The second part $\mathrm{R_8} \cdot \sum_{i=1}^{7} \dot{V}_{i,S} \cdot x_i$represents the pressure loss of the common used elements like the liquid-air cooling system.

Knowing pressure $p_{i,S}$ and volume flow rate $\dot{V}_{i,S}$, interpolation of the rotational speed $n_{i,S}$ of pump i is possible. The diagram is shown in the upper part of. 2. In the lower part of this figure, the relationship of volume flow rate $\dot{V}_{i,S}$, rotational speed $n_{i,S}$ and power consumption $P_{elec\ i,S}$ of pump i is given. With all these constraints in mind, it is possible to solve the mixed integer non-linear programming problem. The problem is mixed-integer because there are variables as x_i or $x_{i,j}$ that are integers, but there also exist variables being continuous, e.g. power consumption $P_{elec\ i,S}$. The problem is non-linear because of equations like (2).

3.3. Solving the problem

Having established the optimization problem, it has to be solved. For this purpose, the Yalmip Matlab Toolbox [9] is used. This toolbox delivers a method to implement the problem in a proper way and provides a variety of solvers. In this case the solver is called ”BMIBNB” and comes with the Yalmib toolbox. This algorithm is an implementation of the branchand-bound method [10] for the integer part of the optimization. The result of the optimization is a known relation between pump and fluid circuit as well as total cost of purchasing and operating the pumps. The optimization is done for a period of five years. The result is

$$\mathrm{x_i} = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{12}$$

and

$$\mathrm{x_{i,j}} = \begin{pmatrix} 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}. \tag{13}$$

From (12), one can see that we must use four pumps for an cost-optimal system. The connection between pump i and fluid circuit j is given in (13). For example, the first row shows, that pump 1 is connected to fluid circuits 3 and 4. They represent guiding right and outer side right. Pump 2 supplies fluid circuits 6 and 7. Fluid circuit 6 is the guiding on the left side and fluid circuit 7 is for the outer side left. The inner side right and the floor, displayed with fluid circuits 1 and 2 are supplied by pump 3. This information is contained in row 3. The last pump is connected to fluid circuit 5, inner side left only. Rows five to seven contain only 0, so no connection from pumps 5, 6 and 7 to any fluid circuit is established. For x_i and $x_{i,j}$ all constraints mentioned in (4) to (8) are fulfilled. The result for the cost function (3) is 1325.14 €. The costs can be separated in purchasing costs with a value of 1000.00 € and energy costs of 325.14 €.

Besides the decision variables x_i and $x_{i,j}$, and the value of the cost function the optimization delivers e.g. rotational speed of pumps, pressure, volume flow rate and electrical power. These data can be used for further investigations.

4. SIMULATION MODEL

This section covers the simulation of the optimized topology of the cooling system and compares it with a cooling system consisting of seven pumps

4.1. Description of the model

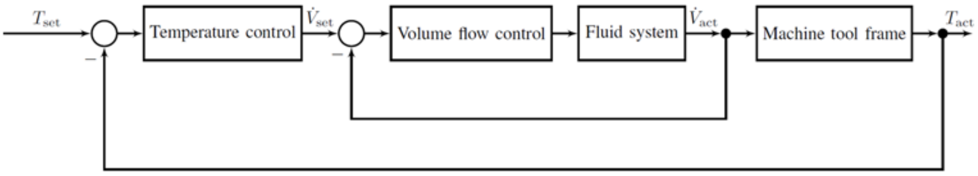

Figure 3: Schematic diagram of the control structure

The simulation model is implemented in Matlab/Simulink R2021a. It consists of a cascaded control loop where the machine tool frame is the plant. Fig. 3 shows the structural design. It is a cascaded controller with a fast volume flow rate control and a slower temperature control. Thus, this system design takes the different time constants between the fluid and the thermal system into account. In analogy, the plant is separated. One part is used to simulate the fluid system with calculation of volume and heat flow through the fluid. The second part is a thermal model of the machine tool frame. For this purpose, the machine tool frame is divided into seven regions according to the fluid circuits. It is implemented as a linear multi-input-multi-output system. Therefore to describe the machine tool frame, 49 transfer functions are necessary. They are based on measurements [11].

Both plants are coupled through the heat flow transported out of the machine tool frame. The heat flow is calculated using (1). However, since the temperature in the return depends on the wall temperature in the machine tool frame, it is given by:

$$T_{\text{return}} = T_{\text{wall}} \cdot \left(1 - \exp\left(-\frac{k}{c_p \cdot \rho \cdot \dot{V}}\right)\right) + T_{\text{flow}} \cdot \exp\left(-\frac{k}{c_p \cdot \rho \cdot \dot{V}}\right) \tag{14}$$

with

$$k = \pi \cdot L \cdot \left(\frac{1}{\alpha_i \cdot d_i} + \frac{1}{2 \cdot \lambda} + \frac{1}{\alpha_o \cdot d_o}\right)^{-1}. \tag{15}$$

The wall temperature T_{wall} comes from the thermal model of the machine tool frame. k contains geometrical and physical information. L is the length of the pipe with an inner diameter d_i and an outer diameter do. The heat transfer coefficients α_i and α_o indicate the capability to transfer heat from the fluid to the steel pipe and from the steel pipe to the machine tool frame. The thermal conductivity λ describes the ability to transfer heat through the wall of the pipe.

4.2. Simulation results

The simulated time is two days. Starting at 0:00 h the first load is applied at 06:30 h when the heat mats are activated with a thermal load of 30 W each. At 12:00 h the infrared light is switched on with a power of 1 kW for three hours. The heat mats are shut down at 21:00 h. This procedure repeats on the second day of the simulation. During the whole time the fluid cooling system is active and supplies the fluid circuits with coolant if it is necessary. The fluid temperature in the flow is constant at 20 °C. The set temperature for the machine tool frame is 21 °C. Independent PI-controller for every fluid circuit are controlling the temperature.

Comparing the temperature behavior of the machine tool frame in case of seven pumps see figure 4 and the optimized one in figure 5 shows the same characteristic. In addition, the temperature deviation from the set temperature is measured with the Euclidean norm also known as L^2-norm:

$$\mathrm{J} = \int_0^\infty e(t)^2 \, \mathrm{dt}. \tag{16}$$

with $e(t) = T_{\mathrm{set}} - T_{\mathrm{act}}$. The difference between the optimized structure and the initial situation is less than 1 %. An interesting point is that despite of a higher volume flow rate the heat flow out of the machine tool frame is constant. This is also observed on experiments performed on the machine tool frame. This behavior is explicable with the low heat conduction of the high performance concrete used to build the machine tool frame. Looking at the energy consumption of the pumps, there is a reduction from 14.82 kWh to 12.66 kWh. With the usage of four pumps the energy consumption can be reduced by 15 %. The power of each pump is shown in figure 6 for the initial system with seven pumps and in figure 7 for the optimized system topology.

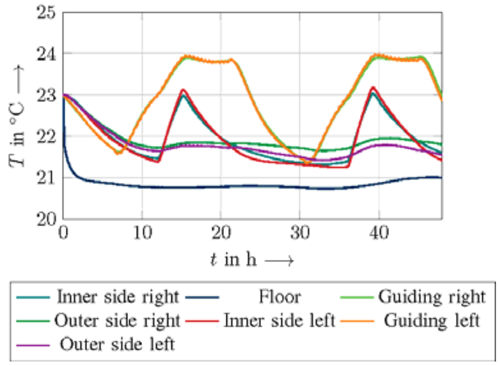

Figure 5: Temperature behaviour of the machine tool frame with seven pumps

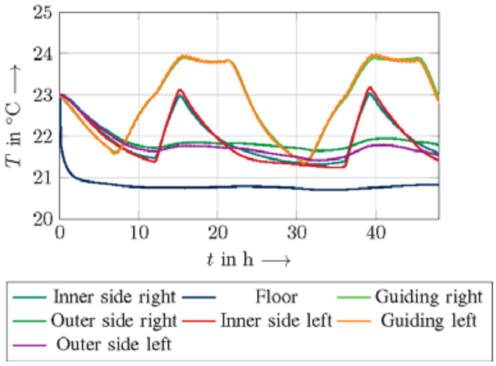

Figure 5: Temperature behaviour of the machine tool frame for optimized structure with four pumps

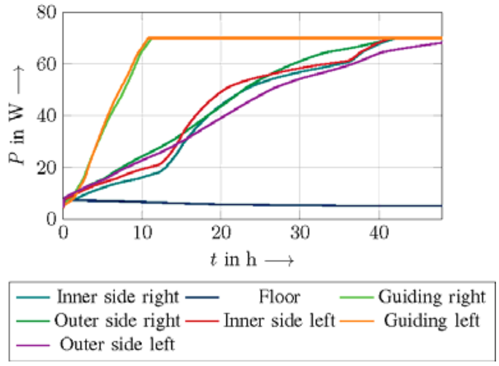

Figure 6: Power consumption for each of the seven pumps

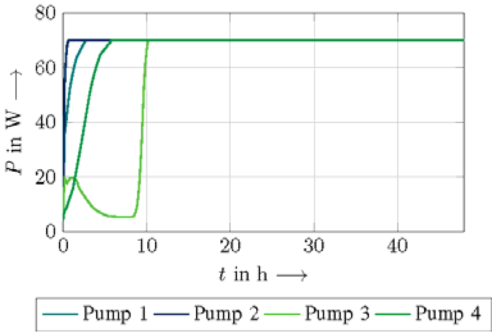

Figure 6: Power consumption for the four pumps of the optimized structure

5. OUTLOOK

In this paper, the optimal topology for a cooling system with seven cooling circuits of a machine tool frame is developed. The result is limited to one pump model. In further work, the number of pump models will be extended. With a variety of pumps, not only the number of them can be determined, but it is also possible to decide which pump is best regarding purchasing cost and energy consumption during operation.

The results are simulated and confirm the energy consumption and the ability to have no negative impact on the temperature field of the machine tool frame. A validation of the optimized structure at the test rig will be performed. Furthermore, an optimization regarding the temperature behavior is in discussion. This has to be performed with help of a FEMmodel of the machine tool frame.

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