Model of Thermal State of the System of Application of Coolant in Grinding Machine

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Abstract. A high grinding performance and ensuring the accuracy and quality of processing depend on a stable thermal regime in the cutting zone, which is carried out by efficient removal of the released heat. Application of lubricating and cooling fluid allows reducing the power and cutting forces, accelerates heat transfer, provides a reduction in temperature in the cutting zone. It's found out, that the most instability is characteristic for the heat entering the machine tool from the coolant system. Potentialities of decreasing of heat fluxes influence at the grinding machine on the accuracy by improving cooling ability of coolant tank are researched. The heat exchange processes in the coolant tank of the grinding machine are studied. A mathematical model describing the temperature regime of coolant in the grinding machine tank is proposed. The model makes it possible to estimate the steady-state and non-stationary temperatures of the coolant in the tank, depending on the course of the stages of the grinding cycle and to define the rational volume of the coolant, considering the cooling of cutting zone, the grinding parameters, and the characteristics of the grinding wheel. The dependence of the value of the average coolant temperature in the grinding machine tank from volume of coolant is determined.

Keywords: Coolant application system · Stationary mode
Nonstationary mode · Temperature gradient · Heat transfer coefficient
Coefficient of thermal conductivity

1 Introduction

An important condition of high grinding performance and ensuring the accuracy and quality of processing is the maintenance of a stable thermal regime in the cutting zone, which is carried out by efficient removal of released heat. This function is performed by coolant—a lubricating and cooling fluid, which reduces the power and cutting forces, accelerates heat transfer, provides a reduction in temperature in the cutting zone.

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Thermal deformations of machines disturb their geometric accuracy and cause errors in the dimensions and shapes of the machined workpieces [1–4]. In addition, the temperature deformations of the grinding machine lead to a deviation from the perpendicular axis of the spindle to the plane of the table [5, 6]. When the temperature changes by 5 °C, the change in the angular position of the spindle axis can be 0.1 mm over a length of 1000 mm. Because of this deviation from the parallelism of the ends of the ground workpiece is 0.012 mm at a length of 300 mm [7]. The factor of the effect of coolant in this process is practically not detected [8].

Analysis of the heat fluxes of the grinding machine shows that the most instability is characteristic for the heat entering the machine from the coolant system [9–11]. For this reason, it is obviously that the actual problem is the reduction of the effect of the heat flows of the machine on the accuracy of grinding, which can be ensured by improving the cooling capacity of the coolant tank.

2 Literature Review

The influence of coolant on the efficiency of the grinding process has been devoted to a large number of studies [6, 7, 12–14].

Shakhnovsky [13] tried to predict the effect of heat fluxes not only directly in the cutting zone, but also as a whole in the technological system of the grinding machine, including in the coolant supply system.

It is established, if the final temperature, returned together with the coolant in the cutting zone, exceeds the ambient temperature by 20 °C, then deviations from the parallelism of the faces of the prismatic part can reach 20 μm. If there is no excess, the deviation from parallelism does not exceed 5 μm.

The reason for this phenomenon is the change in the angular position of the grinding wheels under the influence of excessive temperatures in the reservoirs of the coolant systems [10, 13, 15, 16]. If the excess temperature exceeds 30 °C, the change in the angular position of the circle can reach 0.3 mm, one of the main reasons for the deviation of the position of the grinding spindle from the machine bases is the insufficient heat dissipation capacity of the reservoirs of the coolant system.

The aim of the research is to improve the parameters of the heat exchange processes in the coolant tank of the grinding machine with an individual feeding into the cutting zone.

3 Research Methodology

3.1 Characteristics and Parameters of the Cooling System Operation Cycle

The temperature of the coolant in the reservoir depends on many factors, the most important of which are:

- overall dimensions and spatial geometric shape of the tank;
- the material of the walls of the reservoir and its heat transfer capabilities;
- the nature of the process of heat exchange between the coolant and the walls of the reservoir, and also between the reservoir and air;
- the properties of the used coolant.

In the process of research, the system of coolant application is considered as the one that works in the following sequence.

The machine is switched on for the first time after a long time and operates for a period of time t_d, that is, during the auxiliary time. The initial temperature of the coolant in the tank is equal to the ambient temperature T_{01} = T_{at}: (Fig. 1).

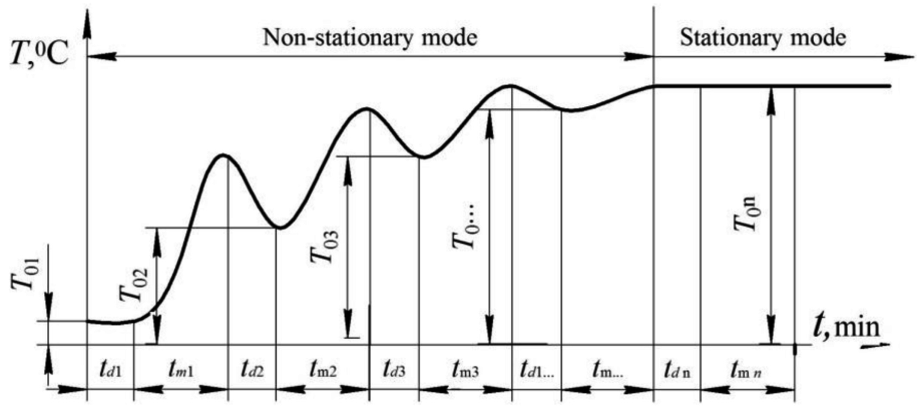

Fig. 1. Diagram of the operation of the coolant system.

After continuous operation for a period of time t_d in the transmission mode, the machine goes into the grinding operation mode, and the coolant application system is operational and operates in it during the main operating time t_m. The temperature at the entrance to the pump is the one that was set at the time of the system's transition to the operating mode – t_d.

Then, the system returns to the throughput mode and is in it during the auxiliary operating time t_d, and the temperature at the pump inlet T_0 = T_{td} is the same as that set in the tank after the first grinding operation, i.e.: T_0 = T_{m1}.

Then, the system again goes into the operating mode, etc., that is, the process repeats cyclically n times, where n is the number of processed blanks.

Total operating time of the system in such cyclic mode can be determined from the dependence:

$$t_{\Sigma} = \sum_{i=1}^{n} \left(t_{di} + t_{mi}\right), \tag{1}$$

where is t_{di}, t_{mi} – respectively, the auxiliary and machine times with i - therefore the repetition of the cycle, min.

The coolant system operates in two thermal modes:

– non-stationary when the current coolant temperature in the tank during the operation of the system for a finite time do not reach a constant value and grows after each next run of the cycle (grinding operation), that is $T_0 \neq const$;
– stationary, when the current coolant temperature in the tank reaches a constant value and remains constant even at $t \to \infty$, that is $T_0 = const$.

When working in non-stationary mode, the temperature at a certain point depends not only on the coordinates of the point, but also on time, that is:

$$T = f(x, y, z, t), \ \frac{dT}{dt} \neq 0, \tag{2}$$

where is $\frac{dT}{dt}$ - the temperature gradient over time.

When operating in a stationary mode, provided the reservoir is of sufficient volume, the temperature does not depend on time, that is:

$$T = f(x, y, z, t), \ \frac{dT}{dt} = 0. \tag{3}$$

In a real coolant application system, the intake part of the pump is located in the reservoir at a horizontal distance from the main heat source - the coolant shower point from the working circuit (Fig. 2).

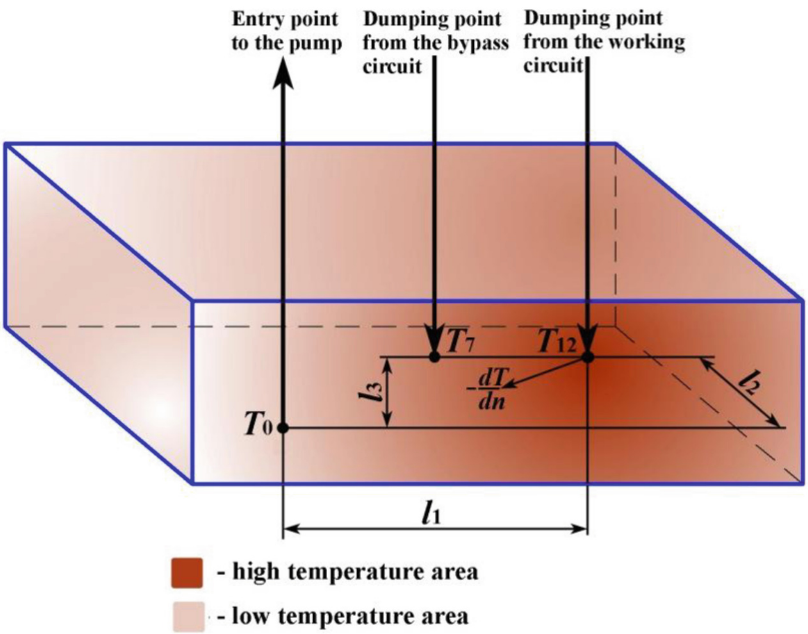

Fig. 2. Diagram of variation of the temperature field in the coolant reservoir.

The temperature decreases with the gradient $-\frac{dT}{dn}$ as you move away from point 12 of the drain from the working circuit. In this case, we assume that the tank used in the system has a sufficient volume, which ensures that the permissible value of the constant temperature is not exceeded.

Considering the above, it is necessary:

- to obtain dependencies for determining the current coolant temperature in the reservoir for a certain value t when the system is operating in non-stationary mode;
- to obtain dependencies for determining the constant coolant temperature in the tank when the system is in steady state operation.

3.2 Mathematical Model of the Thermal State of the Coolant System

In the studies, the heat balance equations in the coolant reservoir were used:

$$Qdt = (cm + c_1 m_1)dT + kF \cdot dt\left(\frac{dT}{2} + T_p - T_{nc}\right), \tag{4}$$

where is Q - the amount of heat that receives coolant in the current (throughput or operating mode), kJ; dT - temperature increase over time dt, °C; T_{nc} - ambient temperature, °C; T_p - coolant temperature in the considered time interval, °C; c - heat capacity of coolant at the current temperature kJ kg^{-1} · °C^{-1}; m - mass of coolant in the tank, kg; c_1 - heat capacity of the tank material, kJ·kg^{-1} · °C^{-1}; m_1 - the calculated mass of the dry reservoir, kg; F - the estimated surface area of the tank, m$_2$; k - coefficient of heat transfer from the tank to the air, W m^{-2} · °C^{-1}.

The calculated surface area for a known volume of the reservoir is determined by the empirical formula:

$$F = 0.065\sqrt[3]{V^2}, \tag{5}$$

The coefficient of heat transfer from the reservoir to the air is determined from the dependence:

$$k = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta}{\lambda} + \frac{1}{\alpha_2}}, \tag{6}$$

where is α_1 – the coefficient of heat transfer from the coolant to the tank wall, W m^{-2} · °C^{-1}; α_2 – coefficient of heat transfer from the tank wall to air W m^{-2} · °C^{-1}; δ = 0.003…0.004 – thickness of the tank wall, m; λ – coefficient of thermal conductivity of the material of the tank wall, W m^{-1} · °C^{-1}.

The values of heat transfer coefficients α_1 and α_2 depend on the type of used coolant and the speed of its movement in the tank, the temperature of the coolant, the walls of the reservoir and the environment, and can vary within fairly wide limits.

The coefficient λ for the most used water-emulsion coolants is usually taken within the limits of λ = 0.15 … 0.65 W m^{-1} · °C^{-1} [12].

In practical calculations of the coolant supply systems for convective heat transfer, with sufficient accuracy, the following coefficients can be adopted:

- k = 75 W $m^{-2} \cdot °C^{-1}$;
- c_1 = 300…500 kJ $kg^{-1} \cdot °C^{-1}$ - for welded steel tanks;
- c – is accepted depending on the temperature according to the reference tables in the range 2 … 4.5 kJ $kg^{-1} \cdot °C^{-1}$.

With the continuous operation of the coolant supply system for the time t, h, the current coolant temperature in the reservoir is determined from the relationship obtained from the heat balance Eq. (4):

$$T = T_{nc} + (T_0 - T_{nc})e^{-\frac{kF}{cm + c_1 m_1}t} + \frac{Q}{kF}\left(1 - e^{-\frac{kF}{cm + c_1 m_1}t}\right), \tag{7}$$

where T_0 the initial temperature of coolant in the tank.

Using Eq. (7), it is possible to determine the temperature of the coolant in the reservoir for anyone when the system is operating in a non-stationary mode.

By the transformation of Eq. (7), with $t \to \infty$ a dependence is obtained for determining the constant temperature in the reservoir when the system is operating in a steady state:

$$T_0 = T_{nc} + \frac{Q}{\sqrt[3]{V^2}}, \tag{8}$$

where is T_{nc} - the ambient temperature, °C; V - volume of liquid in the tank, dm^3;

The value Q is determined by the formula:

$$Q = 860 N_{pid} t, \quad \text{kJ}, \tag{9}$$

where is N_{pid} - the system power input, kW; t - pump running time in the current mode, h.

As previously stated, the system operates in two modes, throughput and operating ones, respectively, the power input in the coolant application system has different values for each of these modes.

When working in the admission mode, formula (9) takes the form:

$$Q = 5,85 \frac{p Q_n t}{\eta_{com}}, \quad \text{kJ}, \tag{10}$$

where is p – the pressure, develops the pump, kg cm^{-2}; Q_n – pump capacity, dm^3 min^{-1}; t – operating time in the transmission mode, min.; η_{com} – full efficiency of the pump.

When the system is operating in the operating mode, in addition to the heat released from its own losses in the coolant supply system, the heat released during the cutting process is added. In this case, the total heat released in the system is determined by the formula:

$$Q = 5.85\frac{pQ_n t_{\text{cut}}}{\eta_{com}} + Q_{LCL}, \tag{11}$$

where is Q_{LCL} – the heat that the coolant receives as a result of cooling the workpiece and the wheel during grinding and is transferred to the tank, kJ; t_{cut} – the main time of this stage of the operation, min.

The value Q_{LCL} depends on the stage of the technological cycle of grinding (tie-in, preliminary, final, grooming), and for the entire operation - it is defined as the total heat at all its stages.

4 Results

The dependencies obtained to determine the temperature are realized as a separate calculation module in the computer program Heat, previously developed by the authors to determine the parameters of the thermal regime of the coolant system. Cycle of computational and analytical studies was conducted with the help of the program.

The studies were carried out for the following data: flow rate 45 dm^3/min, operating pressure 0.06 MPa; type of coolant – Ukrinol-1 with a concentration of 3%.

For this study, the parameters of the cutting regime for grinding were taken as in Table 1.

Table 1. Range of parameter values in determining the cutting force at different stages of the grinding cycle.

Preliminary infeed speed $V_{vr\ n}$ (mm/min)	End infeed speed $V_{vr\ oc}$ (mm/min)	Speed of the part V_{det} (mm/min)	Grain circle number z	Speed diamond with straightening S_{pr} (mm/min)	Cutting depth when adjusting the circle t_{pr} (mm)	Circle hardness (sound index) ZI
1…2	0.1…0.25	30…70	16…40	60…300	0.01…0.03	1.38…1.6

Grinding was performed around a circle with a width of B = 40 mm, hardness of SM2. The preliminary grinding time is 60 … 90 s, the final grinding time is 40 … 60 s.

In order to determine the transition points from non-stationary to stationary, the continuous operation of the coolant system in the operating mode (without transition to the throughput) was investigated.

The results of the studies are shown in the form of graphs of these temperatures in the screenshot of the graphic window of the Heat program (Fig. 3).

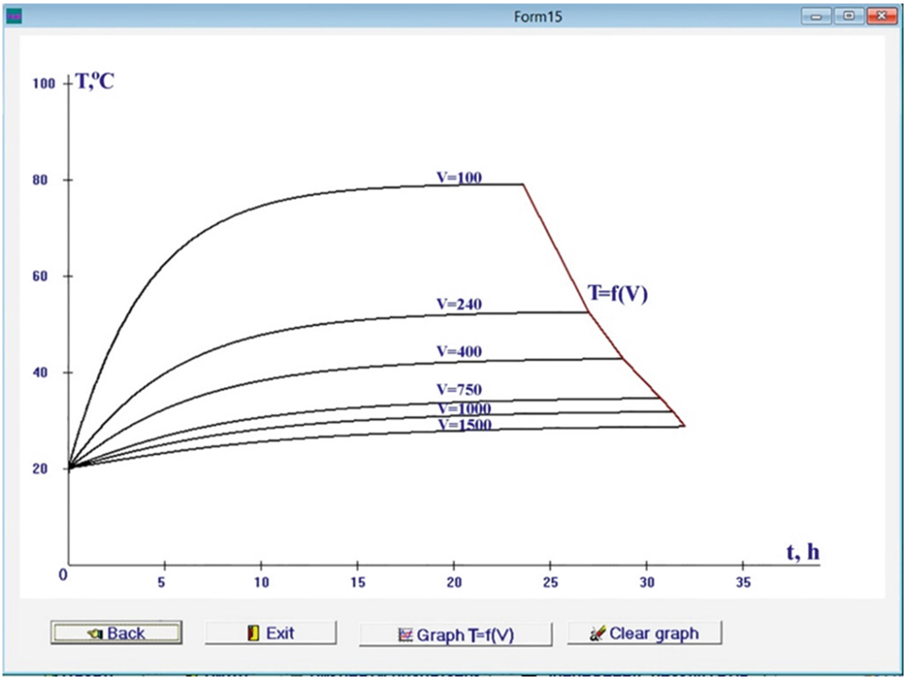

Fig. 3. Graphs of temperature change of coolant in the tank.

Analysis of the temperature graphs in the coolant tank shows that they have a special shape, which consist of two sections: a curve characterizing the operation of the coolant application system in a nonstationary regime and almost a straight line, asymptotic approaching a horizontal line of stable temperature characterizing the operation of the system in a steady state.

Analysis of the results shows that the increase in the coolant temperature after heat exchange with the billet and the ring is explained by the high heat transfer in the grinding process, especially in the preliminary grinding stage, where the temperature even in the application of coolant fluctuates in the range 200 … 900 °C.

Obviously, for the adopted parameters of the coolant application system, the condition for maintaining the average temperature of the coolant within 25 … 35 °C in the reservoir should be 400 … 1500 dm^3.

The transition points from the nonstationary regime to the stationary one are established (Table 2).

As can be seen from the graphs, with the accuracy of the calculation of the temperature 0.001, the coolant supply system operates in a non-stationary mode from 24 to 32 h, and this time increases with the increase in the volume of the reservoir, due to the greater inertia of heat exchange in a larger volume of liquid. At the same time, at practically reasonable accuracy of calculation of temperature 0.5 … 1.5 the time of system operation in non-stationary mode will decrease to 5 … 12 h.

Table 2. Parameters of the transition points of the coolant application system from nonstationary to stationary.

Reservoir volume V (dm^3)	Time to exit non-stationary mode (h)	The value of stable coolant temperature (°C)
100	23.58	82.39
240	27.00	54.69
400	28.81	44.58
750	30.73	36.02
1000	31.40	33.15
1500	32.02	29.91

The study shows that the tools for ensuring a rational thermal regime of the coolant system are the selection of the required volume of the reservoir and the corresponding characteristics of the pump based on the automated calculation of the temperature conditions of the coolant with the help of the developed software.

5 Conclusions

1. The research described a mathematical model describing the temperature regime of coolant in the grinding tank in the working and throughput modes. The model makes it possible to estimate the steady-state and non-stationary temperatures of the coolant in the reservoir, depending on the course of the stages of the grinding cycle.
2. The results of calculations and analytical studies carried out on the basis of the model make it possible to determine the rational volume of the coolant in its application system, taking into account the cooling zone cooling rate, the grinding parameters, and the characteristics of the grinding wheel.
3. It is established that the stabilization of the thermal regime of coolant comes after
4. 5 … 30 h of operation of the grinding machine with an accuracy of determining the steady-state temperature of 0.5 … 0.001, which allows using the results of studies in the development of algorithms and means for compensating the temperature deformations of machines during processing precision parts.
5. The results of the studies are recommended for application in the development of standards for the volume of coolant in its application systems for grinding machines.

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