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EXPERIMENTAL INVESTIGATION OF CRYOGENIC INTERNAL COOLING WITH COMPARATIVE ANALYSIS FOR DIFFERENT SPINDLE CONCEPTS IN MACHINING

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Abstract
The increasing demand for work pieces made out of difficult-to-machine materials and for high performance machining parameters, as well as stricter environmental requirements, are driving the machining industry's needs for alternative cooling lubrication strategies. Cryogenic cooling is therefore an innovative approach to improve process performance and sustainability. For example, liquid carbon dioxide (LCO_2) can be used as a cryogenic medium for process cooling with the option of cryogenic minimum quantity lubrication (cMQL). As part of this research, the effects of the internal supply of CO_2 through the spindle on the cooling capacity and on the spindle itself are investigated in a test setup. Before the LCO_2 enters the spindle, it can be stabilized in its density by adapting the CO_2 pre-cooling temperature to ensure the highest possible constant cooling capacity and adaptive control of the cooling capacity through the spindle. The main tests focus on the filling and evacuation of the spindle with the cryogenic medium at the start and end of the machining process or during tool changes. In addition to the time required for filling and evacuation, the main research criteria are the monitoring of the spindle temperature at the spindle inlet and outlet. Low spindle temperature due to expansion of the LCO_2 in the spindle can be avoided by flushing with gaseous CO_2. The investigations of spindle temperatures and filling and evacuation times compare both a one-channel and a two-channel spindle concept, as well as the orientations of the machine tool's main spindle in a horizontal or vertical design.

Keywords:
Cryogenic cooling, Spindle integration, Machining

1 INTRODUCTION

The increasing importance of environmentally friendly and resource-efficient production in industry requires innovative and sustainable machining processes. Due to the increasing demand for lightweight construction in almost all sectors, materials that are difficult to machine such as titanium or nickel-based alloys for high temperatures are increasingly being used. With conventional cooling lubricant concepts, these materials can only be machined at great expense of resources. The most common cooling concept is high-pressure wet machining ($p > 80$ bar). This involves the use of large quantities of water, cooling media and chemical additives, which are considered harmful to the environment and to health. Due to the high consumption of cooling lubricants in machining, approx. 66 000 tons of hazardous waste are produced in Germany every year [Bafa 2021]. One option for a sustainable cooling concept is cryogenic process cooling. In this cooling concept, cryogenic media such as nitrogen (N_2) and carbon dioxide (CO_2) are used to cool the process zone during machining. The cryogenic medium evaporates during cooling without leaving any residue. This offers a huge potential due to the elimination of cleaning steps afterwards and also enables the cooling of processes in which no cooling media can be used due to contamination requirements (e.g. in the field of medical technology) or the effects on the material (e.g. swelling of plastic). Cryogenic cooling can therefore also be used for processes that are currently machined dry and contributing to lower tool wear, better chip breaking behavior and better surface qualities through cooling. By combining cryogenic cooling with minimum quantity lubrication (MQL) and for cMQL the extraction and preparation of conventional lubricants as well as subsequent processes such as chip cleaning can be eliminated [Gross 2021]. The reduction in the use of resources and the use of ecological alternatives as part of the cooling lubricant supply are an important step in the transformation to a more sustainable industrial environment. In the area of machining with geometrically defined cutting edges the spindle integration for internal tool cooling is essential for the effective supply of cooling lubricant media to the single tool cutting edge.

2 STATE OF THE ART

2.1 Cryogenic cooling

Cryogenic cooling describes the use of cryogenic media, e.g. N_2, CO_2 or Helium in a temperature range from 0 K to 0 °C. As pure cryogenic cooling is often not sufficient for machining, it is necessary to add minimum quantity oil lubrication to the cooling process. The number of scientific papers on cryogenic cooling has been steadily increasing since 1999. Initial studies focused on liquid nitrogen (LN_2), which cools at up to ϑ = -196 °C [Wang 2000]. As a result of the fact that tool wear could be reduced in difficult-to-cut alloys such as Ti-6Al-4V or X5CrNi18-10, the range of materials was constantly expanding. Since *De Chiffre* investigated the influence of CO_2 as a cooling medium in grinding and *Hesterberg and Wittkop* in turning, CO_2 has been increasingly used as a cryogenic cooling medium [De Chiffre 2007; Hesterberg 2005]. Furthermore, the low temperature level of LN_2 prevents the mixing of conventional lubricating media, as these would freeze prematurely. A cMQL based on LN_2 therefore requires the separate supply of nitrogen and MQL. In contrast, CO_2 reaches a temperature minimum of ϑ = -78.5 °C. Another advantage is that CO_2 can be liquefied under pressure and at room temperature without the need for cooling and stored in riser tube bottles without any further technical effort. This means that oil can be injected directly into the CO_2. The cooling performance of the CO_2 is based on the Joule-Thomson effect. The CO_2 is fed through a line with constant pressure to the outlet point. There, a pressure drop and expansion take place, which initiates an energy transformation and realizes a cooling effect down to ϑ = -78.5 °C [Wagner 2013]. In contrast to conventional metalworking fluids, CO_2 only realizes the cooling function in the machining process, so that additional support with MQL can further improve performance and the machining result [Bagherzadeh 2018; Gross 2021; Park 2017; Pereira 2016; Meier 2021a].

2.2 CMQL mixing and delivery systems

CMQL systems for media supply differ fundamentally in the cryogenic media used (LN_2, CO_2), their aggregate state and the type of supply (external/internal and single/multi-channel). The cryogenic (carrier) medium and the lubricant can be fed to the processing zone via a one- or two-channel system. In addition, a distinction must be made on whether the machine integration is realized through an external nozzle or an integration into the machine tool spindle for supply through internal cooling channels of the tool, especially for milling and drilling. In the two-channel system, compressed air is also required to carry the oil. The large number of media and additional channels increase the complexity of the system and make the integration of a two-channel system into the machine tool more challenging. [Duchosal 2015; Pereira 2015].

In a one-channel system, both media are fed to the process zone as a mixture in one line, as in the MQL. In the field of machining with geometrically defined cutting edges (milling, turning, drilling), it has already been proven that a homogeneous mixing ratio of CO_2 and oil is not required to efficiently cool and lubricate the cutting zone. [Hanenkamp 2018; Gross 2020; Meier 2021b]

Although it is not absolutely necessary for the lubricant to be homogeneously distributed in the liquid CO_2 for a stable machining process, the choice of lubricant does have an influence and should be specifically investigated for each application. Furthermore, bio-oils can be used for the cMQL, which are otherwise hardly used or not used at all due to their tendency to oxidize and polymerize during machining. This can therefore make an important contribution to the sustainability of machining processes. [Meier 2021a; Meier 2021b]

However, the homogeneous miscibility of CO_2 and oil is a basic assumption for the use of supercritical ($scCO_2$). Therefore, the choice of oils that can be used in $scCO_2$mixing systems is severely limited, as the homogeneous miscibility of the two media must be proven in advance for each oil.

In contrast to the cMQL mixing system developed at the Institute for Ressource and Energy Efficient Production Systems (REP), current patents and (resulting) commercially available cMQL systems use CO_2 in a supercritical state or increase the pressure of the cryogenic medium in order to achieve a low-pulsation and stable supply of CO_2 to the cutting edge of the tool. *Fusion Coolant* relies on $scCO_2$ in its PureCut+ system. In addition to further pumps, energy-intensive heating elements are required for this system to ensure the supercritical state [Supekar 2012]. In the ChilAire system from *Cool Clean Technologies*, both the liquid and the gaseous phase of the CO_2 are used and the pressure of the CO_2 is increased [Schiller 2006]. Both two-channel systems BeCold from *HRE-Automation* and AerosolMaster 4000 Cryolub from *Knoll*, formerly *Rother Technologie*, are existing pure MQL systems that are expanded with a separate supply line for the LCO_2. [HRE 2020; Rother 2013]

The single-channel cMQL mixing and supply system developed by the REP Institute in 2018 has already been used in a large number of industrial and research projects and has been continuously developed [Hanenkamp 2018]. It has been demonstrated that no supercritical or gaseous state is required to use CO_2 as a carrier medium for a cMQL technology [Gross 2021]. For the REP one-channel cMQL mixing and delivery system, liquid CO_2 is taken from a riser tube bottle bundle. A high-performance liquid chromatography pump delivers oil at up to $\dot{m}$ = 50 ml/min, which is injected into the CO_2 stream at higher pressure and transported to the process zone as a mixture. The CO_2 mass flow, density and temperature are measured via a Coriolis sensor, shown on a display for monitoring and can be saved optionally. The oil flow rate can be adjusted from $\dot{m}$ = 0.001 ml/min to 50 ml/min.

2.3 Spindle integration

With the commercial cMQL systems presented, it is possible to supply a machine tool with both CO_2 and MQL. The systems can currently only be used for the internal cooling of cutting tools at considerable expense and with an assessment of safety risks. A major hurdle to the successful establishment of cryogenic strategies particularly in the manufacturing industry is currently that no standardized holistic solution (cMQL system, rotary union, spindle, tool transfer, tool) is offered for the integration into the machine tool. Retrofitting of existing machines or the purchase of a new machine tool is associated with high investments.

There are basically two possible solutions for the spindle design, such as the type of feed of the cMQL systems, which are firstly a one-channel spindle or secondly a two-channel spindle. These differ in the supply of the different media, which are either fed to the tool in one channel or in separate lines, see Fig. 1. In the two-channel spindle, the coolant and lubricant are fed separately to the cutting edge. At best, this integration requires the continuation of the two separate cooling channels in the tool. The lines in a two-channel spindle differ primarily in terms of their internal diameter. The thinner line can be used for cryogenic cooling as it has a lower mass flow rate. The larger second line, on the other hand, is used for the MQ-aerosol.

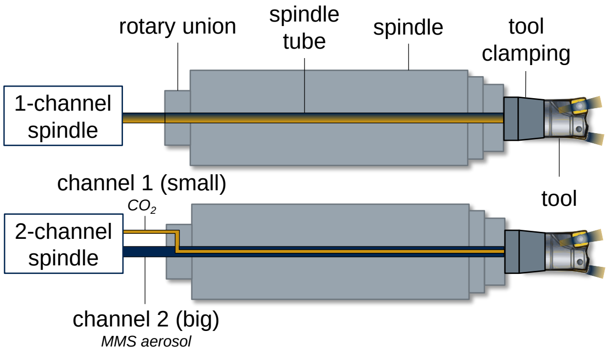

Fig. 1: One or two-channel spindle design.

In many state-of-the-art applications, due to the challenges described above, only one external nozzle is typically used to feed the cryogenic fluid or the one- or two-channel cMQL. The use and integration of the external nozzle into the machine is technically easy to implement and is usually attached to the spindle by means of an articulated arm. The supply lines only need to be installed in the machine, but do not have to be integrated into the rotating spindle. However, the external nozzle restricts the machining process because it is ideally located 20-40 mm from the tool, creating an interfering contour. Deep grooves may not be supplied with coolant, and the nozzle may collide with the workpiece if the cutting depth is too large. Drilling processes also require an internal supply of coolant and lubricant, both to remove chips and to allow coolant to reach the process zone deep in the workpiece.

This creates the need to develop an industrially suitable and automatable integration for the use of cryogenic cooling with automatic tool change in the machine. The challenge here, especially with cryogenic cooling, is the machine tool spindle, which is under high pressure. Pressure reduction in the spindle takes a long time and leads to strong and undesirable cooling of the spindle components during CO_2 expansion. For this reason, the study has developed and thoroughly analyzed a concept for pre-flooding and flushing, which is mainly used at the beginning and end of the process. Pre-flooding means that the spindle tube is pre-filled with gaseous CO_2 and flushing means that the liquid CO_2 phase is evacuated from the spindle tube with gaseous CO_2.

3 EXPERIMENTAL SETUP

This paper investigates how liquid CO_2 can be supplied from the rotary union of a machine tool spindle to the tool holder for internal tool cooling without excessive cooling of the spindle due to expansion of the liquid carbon dioxide. To this end, two basic concepts are examined in the following experiments. The first concept eliminates the need for a spindle modification and an additional line, and allows the CO_2 to flow directly through the existing spindle chamber. This concept is therefore referred to as 'one-channel'. The second concept includes an additional thin line for cryogenic cooling that is drawn into the existing spindle chamber for the conventional coolant and requires a spindle modification. This concept is therefore called 'two-channel' and MQL oil and CO_2 are fed in separate lines.

With the one-channel concept, the spindle chamber can be pre-flooded and flushed. The spindle tube is represented by a stainless steel tube of the same length and diameter as a representative milling machine spindle in the test setup. The milling tool or the cooling channels of the tool are always represented by a nozzle with an outlet of d_i = 0.3 mm. This is necessary to generate a realistic dynamic pressure (as in machining through the smaller internal cooling channels of the tool). The study compares a vertical and a horizontal orientation of the spindle.

The following subsections explain the experimental setups used to collect data and how the tests were performed. In order to bring the CO_2 into a stable state with a constant high density, the CO_2 is pre-cooled before entering the spindle in all test series. The pre-cooling system described below is based on extensive preliminary work and fundamental investigations at the REP Institute. [Meier 2023; Meier 2024]. Three Bronkhorst Coriolis sensors are used as measuring instruments in all test series. They can be used to measure the flow rate, density and temperature of both liquids and gases. All data recorded every Δt = 0.2 s in this work were recorded using the NI PXIe-1092 measurement technology PC.

3.1 Experimental setup for pre-cooling

For the test series, it is necessary to pre-cool the carbon dioxide leaving the CO_2 bundle at room temperature. For this reason, a cooling section (l = 4 m) was constructed, in which the CO_2 line runs in a larger cooling water pipe of a heat exchanger and cooling water flows through the cooling water pipe in a temperature-controlled circuit according to the counter flow principle. The aim of the pre-cooling series of experiments is to find out which cooling water temperature is best suited for this experimental setup at different CO_2 mass flow rates and how the temperature of the cooling water affects the density of the carbon dioxide at the nozzle. [Meier 2024].

A bundle of riser tube bottles provides the liquid CO_2 for the experiments, see Fig. 2. Behind the bundle is a shut-off valve (V_S) to interrupt the CO_2 flow and the first Coriolis sensor (C1) to provide data on the CO_2 mass flow provided by the bundle. Another Coriolis sensor (C2) is installed after the cooling section in order to be able to quantify the effect of the cooling section precisely with measured values directly before and after the cooling section. The following flexible line with a length of l = 4 m and an inner diameter of d_i = 3.2 mm is used to represent a supply line from the cooling section through the cable drag to the rotary union of the machine spindle, as it could later be installed in a machine tool. If there is sufficient space in the machine tool, the cooling section can be integrated directly in front of the rotary union. A third Coriolis sensor (C3) is located behind the 4 m long flexible supply line in order to be able to determine the influence of the longer pipe length (e.g. in the cable drag or alternative supply to the spindle) on the properties of the carbon dioxide. The throttle valve (V_T) in front of the nozzle can be used to set different flow rates. The five different flow rates $\dot{m}$ = 3/5/7/9/11 kg/h are tested and the cooling water temperature is lowered from room temperature ϑ_{max} = 21 °C to ϑ_{min} = 3 °C in steps of $\Delta\vartheta$ = 1 °C. The mass flow, density and temperature of the carbon dioxide are measured at the three Coriolis sensors (C1-C3).

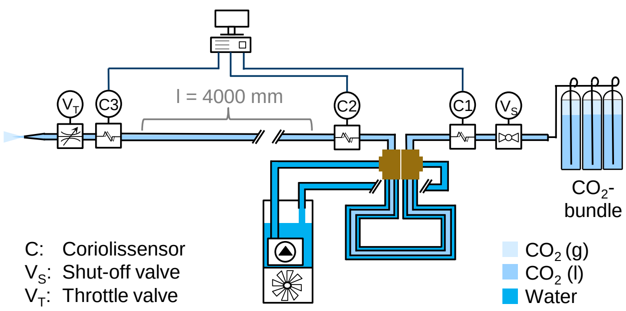

Fig. 2: Experimental setup for pre-cooling.

3.2 Experimental setup one-channel integration

The goal of the one-channel integration test series is the investigation of the effect of pre-flooding/flushing on the filling/evacuation times as well as the temperature curves and the influence of the spindle orientation (horizontal/ vertical). The pressure gauge (M) is used to determine the pressure curve in the pipe at any time, as shown in Fig. 3. The temperature curves at selected points are recorded by three thermocouples (yellow markings). The test setup, consists of a supply line for liquid CO_2, a supply line for gaseous CO_2, the spindle tube, and the outlet side with nozzle. The liquid CO_2 supply line begins on the right with the riser tube bundle. This is followed by the cooling section, a shut-off valve (V_{S1}) and a Coriolis sensor (C1). The supply line for gaseous CO_2 begins on the right with a CO_2 gas bottle. A second shut-off valve (V_{S2}) and a Coriolis sensor (C2) are installed behind it. The two lines are connected by a T-piece with the stainless steel pipe (l = 1.1 m, d_i = 7.0 mm), which represents the chamber of a machine spindle from the rotary union at the inlet to the tool holder at the outlet for the one-channel concept.

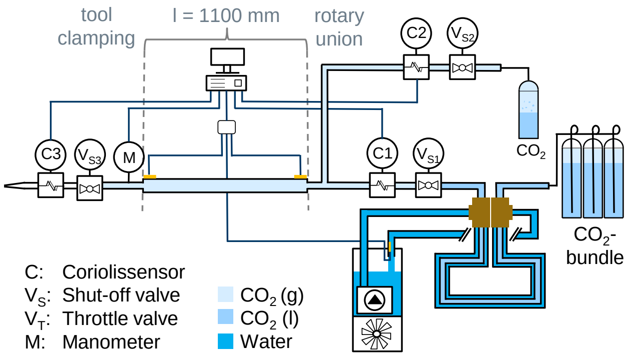

Fig. 3: Experimental setup one-channel integration.

Thermocouples are attached to the outside of the stainless steel tube on the inlet side, where the spindle tube cross section is enlarged, and on the outlet side, where the tube cross section is reduced. A third thermocouple monitors the cooling water temperature (ϑ_W = 10 °C). A pressure gauge (M) is installed next to the stainless steel tube. The recorded data on the pressure in the pipe is particularly useful for determining the start/end points of the filling/evacuation times. The valve (V_{S3}) allows either full flow or no flow. The Coriolis sensor (C3) is the last instrument before the nozzle and records data on the liquid or gaseous CO_2 as it passes through the stainless steel tube just before it exits at the nozzle. In order to determine if the filling/evacuation times of the stainless steel tube can be reduced and what influence the orientation (horizontal/ vertical) of the test setup has, the spindle chamber is pre-flooded or flushed with gaseous CO_2. The filling time starts with the criterion of the pressure increase on the pressure gauge (M) after the spindle and the filling time is stopped when the CO_2 density at the last Coriolis sensor in front of the nozzle is C3 = 90 % of the maximum density ϱ_{max}. The evacuation time starts with a pressure drop at (M) and is stopped when the flow rate at C3 is < 1.3 kg/h.

3.3 Experimental setup two-channel integration

For the two-channel test setup, PEEK tubes of different diameters are used in the test setup instead of the stainless steel tube. The PEEK tubes represent the inner part of the two channels, through which pure CO_2 is fed as in the two-channel machine integration. In the outer channel, i.e. the area between the so-called lance with the inner CO_2 channel and the actual spindle tube, the MQL aerosol would flow. For reasons of comparability and completeness, this test series will also collect data for the stainless steel tube from the one-channel concept. The purpose of this series of tests is to determine how long it takes to start and stop the CO_2 flow for the different cooling channel diameters and what cooling capacity is achieved in the static state.

As in the previous test setups, three Coriolis sensor (C1-C3), one pressure gauge (M) and the three thermocouples are used. An additional thermocouple and an ampere meter, which measures the current at the power supply cable of the heating plate, are also used. Quantification of the cooling capacity is performed with a heating plate placed at a distance of l = 20 mm behind the nozzle. It is heated to its maximum temperature ϑ_{max} = 95 °C before the start of each test. During the measurement, the CO_2 cools the heating plate, so it has to be reheated. The power required to reheat the heating plate can be equated to the cooling power of the carbon dioxide. The experimental setup for measuring the cooling capacity has already been developed and investigated in preliminary studies by the REP Institute [Meier 2023; Meier 2024].

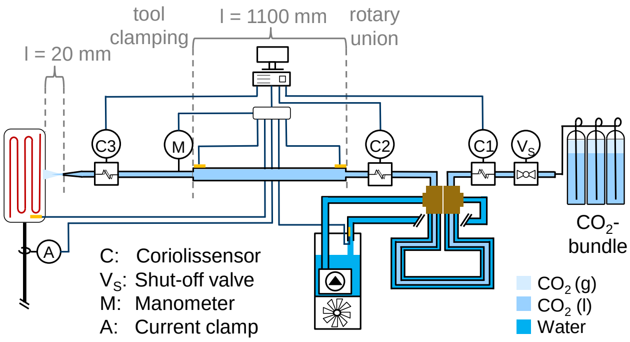

Fig. 4: Experimental setup two-channel integration.

The test setup, as shown in Fig. 4, is similar to the 'pre-cooling' test setup. Compared to the 'one-channel Integration' test series, the gaseous CO_2 supply line has been omitted, since no pre-flooding or flushing is required. The test setup therefore consists of the familiar liquid CO_2 supply line, the cooling channel simulated with various lines, and the nozzle at the outlet. Thermocouples are only glued to the inlet and outlet of the stainless steel tube, as the thermocouples cannot be reliably attached to the thinner PEEK tubes. In addition, temperature measurement is not necessary for the two-channel design because the smaller pipe diameters mean that there is no expansion on the way through the spindle and the second outer channel also acts as an insulation. The remaining two thermocouples are used to monitor the temperature of the cooling water in the cooling section and the heating plates. The cooling water temperature is ϑ_W = 10 °C. The pipe representing the spindle tube between the rotary union and the tool clamping is varied. PEEK tubes with d_i = 0.50/0.75/1.00 mm and the stainless steel tube with d_i = 7.00 mm are used for the tests. Filling, the static state, and evacuation are recorded. The tests are performed in horizontal and vertical orientation.

4 RESULTS

The results of the three sets of tests on precooling and one and two-channel spindle integration are discussed in the following subsections.

4.1 Results for pre-cooling

The pre-cooling test series focuses on determining the pre-cooling temperature of the water bath required to increase the density of the CO_2 in the supply line to a stable level of more than ϱ = 800 kg/m³. For this purpose, the behavior at different cooling water temperatures as a dependent of CO_2 flow rates is considered and measured with a Coriolis sensor (C2). In addition, the density is measured again after a subsequent additional flexible pipe with a length of l = 4 m (C3) in order to investigate whether the density is still sufficiently high afterwards.

The results are shown in the Fig. 5. The values of the Coriolis sensor (C2) directly after the CO_2 pre-cooling are shown with solid lines and the values at the sensor (C3) after the additional second line are shown with dashed lines. At the lowest pre-cooling water temperature of ϑ_{min} = 3 °C and the lowest mass flow rate of $\dot{m}$ = 3 kg/h, a maximum density of over ϱ_{max} = 900 kg/m³ can be achieved. This corresponds to more than a doubling of the density compared to the initial state of less than ϱ = 400 kg/m³. Even at the highest mass flow rate of $\dot{m}$ = 11 kg/h, the required density limit of more than ϱ = 800 kg/m³ can be achieved with a pre-cooling water temperature of ϑ = 12 °C, both at measuring point (C2) and at (C3). For the following tests, a pre-cooling water temperature of ϑ_W = 10 °C is chosen in order to guarantee a consistently high density for all tests, even with higher CO_2 mass flows and higher fluctuations in the CO_2 density from the bundle.

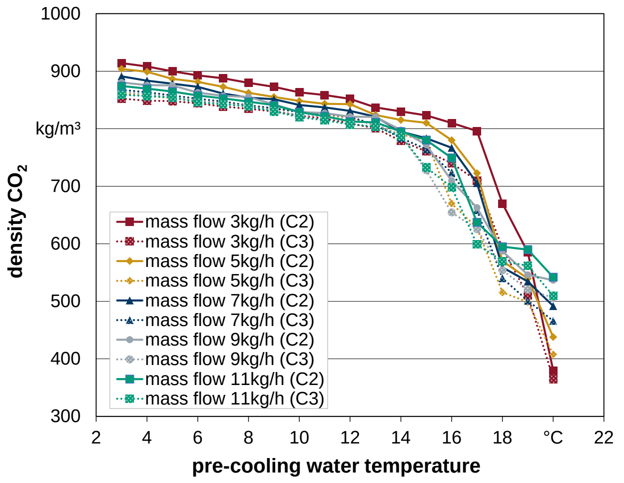

Fig. 5: Influence of pre-cooling temperature on CO_2 density.

In addition, it can be shown that pre-cooling the CO_2 not only increases the density of the coolant as a function of the cooling water temperature, but also reliably compensates strong fluctuations in the density of the bundle, s. Fig. 6.

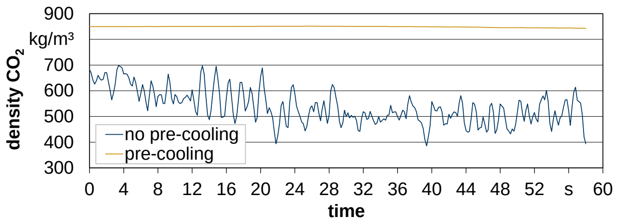

Fig. 6: Stabilization of CO_2 density through pre-cooling.

4.2 Results for one-channel integration

The test series for the one-channel spindle integration deals with the question whether it is reasonable to pre-flood or flush the volume of the stainless steel tube (representing the spindle chamber) with gaseous CO_2 during filling and evacuation. The filling and evacuation times of the tube and its temperature development at the tube inlet are used for the evaluation. It is also checked whether the results depend on the spindle orientation (horizontal/vertical). The summarized evaluation of the filling and evacuation time tests is shown in Fig. 7.

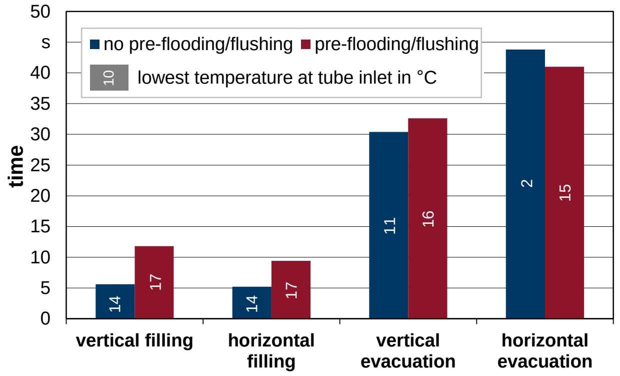

Fig. 7: Filling/evacuation times for one-channel integration.

The filling process is more than three times shorter than the evacuation, regardless of the use of gaseous CO_2 for pre-flooding, the orientation and the flow condition. When comparing vertical and horizontal filling, there is no clear difference between the times. However, filling in horizontal orientation tends to be slightly faster. The same comparison for evacuation shows that vertical evacuation is significantly faster (up to 44%) than horizontal evacuation. Pre-flooding doubles the filling times in both orientations. When evacuating in a vertical orientation, flushing only results in an insignificant increase in time. In contrast, when evacuating in a horizontal orientation, flushing can save time.

Evacuating the stainless steel tube generally takes longer than filling it, as the liquid CO_2 begins to expand when the pressure in the tube drops, thus partially maintaining the mass flow at the nozzle. In vertical evacuation, gravity helps the liquid CO_2 phase which is separated from the gaseous phase to flow out of the pipe. In the horizontal case, this support is missing, so the liquid phase remains in the stainless steel pipe and gradually expands due to the falling pressure and rising temperatures. At the same time, horizontal flushing saves more time than vertical flushing because the liquid phase in the stainless steel pipe is flushed out by the gas phase. This prevents a significant temperature drop as the liquid CO_2 does not expand in the pipe. During the horizontal evacuation process, very low temperatures of ϑ = 2-3 °C occur at the spindle tube inlet without flushing. With flushing, the temperature is ϑ = 13-15 °C. During filling, the temperature difference between no pre-flooding and pre-flooding is only $\Delta\vartheta$ = 3 °C.

The following discussion will focus on the evaluation for the horizontal orientation of the spindle because the effects of pre-flooding and flushing are more significant here. However, for comparison purposes, the test results for the vertical orientation are also shown on the right side of the figure. Fig. 8 shows the time-flow-temperature curve for the horizontal (left) and vertical filling (right), once without (top) and once with (bottom) pre-flooding. It can be seen that the temperature at the pipe inlet drops by approx. $\Delta\vartheta$ = 4.5 °C as soon as the liquid CO_2 is turned on. This relatively small temperature drop lasts only a few seconds and is quickly compensated by the ambient heat. In Fig. 8 (bottom left), a narrow peak in the flow of gaseous CO_2 can be seen before the flow rate of the bundle increases, indicating pre-flooding. When the liquid phase subsequently flows in, there is no sudden drop in temperature. This difference can be explained by the pressure conditions in the stainless steel pipe. Without pre-flooding, there is only atmospheric pressure in the pipe when the liquid phase enters, so the CO_2 expands from the liquid to the gaseous state at the point where it enters the pipe. During this expansion, the inlet of the stainless steel pipe is suddenly cooled.

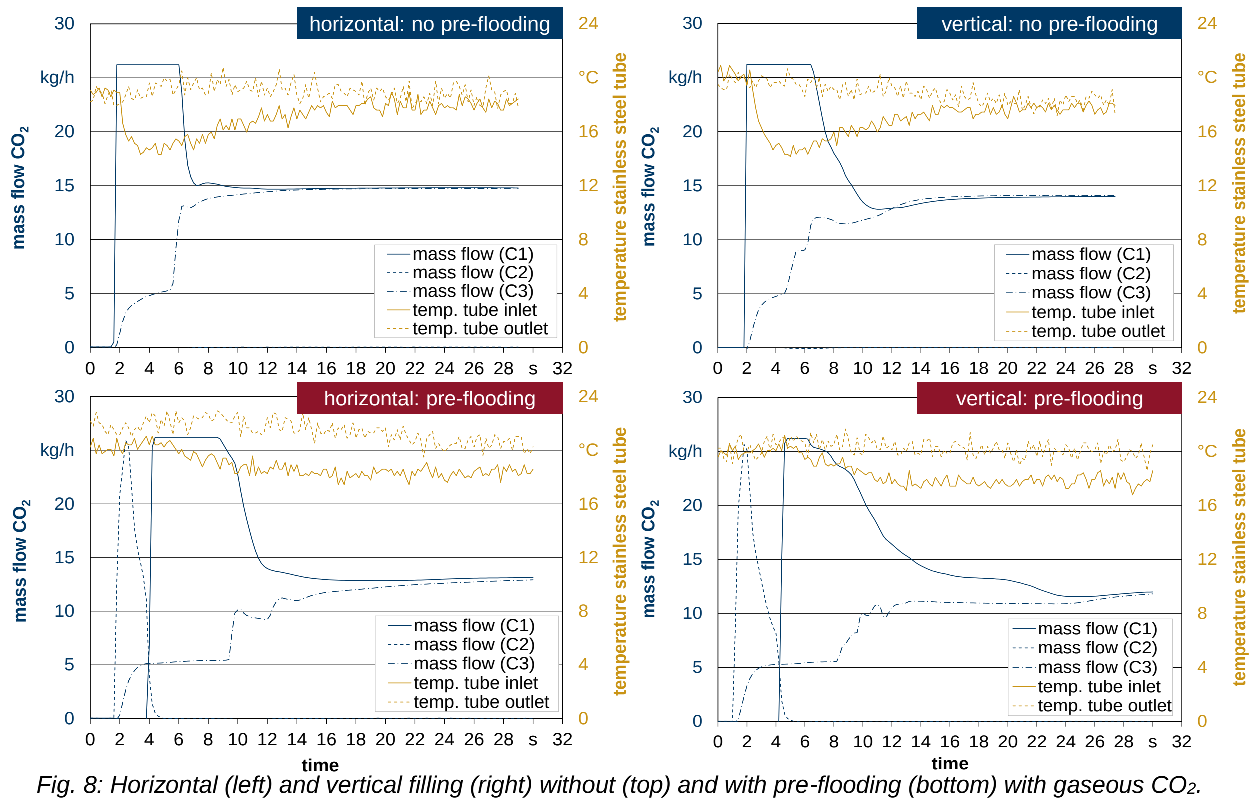

Fig. 8: Horizontal (left) and vertical filling (right) without (top) and with pre-flooding (bottom) with gaseous CO_2.

The expansion, and therefore the cooling, is only temporary as the expanded CO_2, with its largely increased volume, suddenly fills the pipe all the way to the nozzle, increasing the pressure in the pipe. This back pressure prevents further expansion of the liquid phase, which pushes the small amount of gas phase through the nozzle. Filling with pre-flooding takes about twice as long as filling without pre-flooding because the liquid CO_2 must push the gas phase out of the stainless steel tube through the nozzle during pre-flooding and subsequent filling. Consequently, it takes longer to push gaseous CO_2 (with a pipe pressure of $p = 50$ bar) through the nozzle than air, which is only present in the pipe at atmospheric pressure. A comparative analysis of the vertical pre-flooding tests shows no significant differences from the results described for the horizontal setup.

In analogy to Fig. 8, Fig. 9 shows the same representation of the time-flow-temperature diagrams for evacuating the stainless steel pipe once without (top) and once with (bottom) flushing.

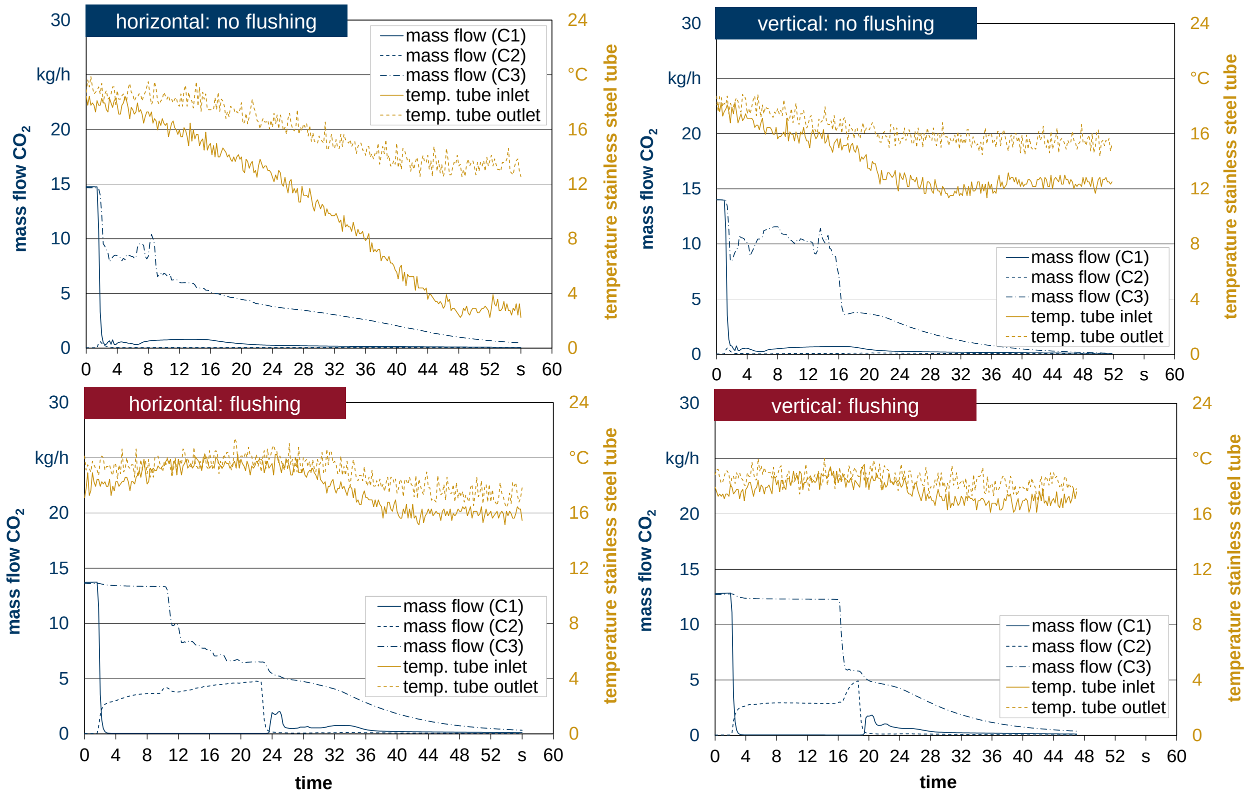

Fig. 9 : Horizontal (left) and vertical evacuation (right) without (top) and with flushing (bottom) with gaseous CO_2.

For evacuation without flushing, the flow rate at the nozzle initially collapses almost simultaneously with the flow rate of the bundle. At approximately $\dot{m}$ = 8 kg/h, the flow rate at the nozzle stagnates, varies, and then increases slightly before declining uniformly toward $\dot{m}$ = 0 kg/h. Since the liquid and gaseous CO_2 supply is shut off at this point, the stagnation or increase in flow can only be caused by expansion of the CO_2 in the pipe. This is also supported by the sharp drop in temperature at the pipe inlet that begins shortly after the bundle is shut off. Over a period of about Δt = 40 s, the temperature drops relatively steadily by about $\Delta\vartheta$ = 16 °C. Only when the flow rate at the nozzle reaches almost $\dot{m}$ = 0 kg/h, the temperature at the tube inlet stabilizes again. The temperature at the pipe outlet starts to fall later and stabilizes earlier. Over a period of about Δt = 24 s, it falls by only about $\Delta\vartheta$ = 6 °C. Flushing with gaseous CO_2 pushes the liquid phase out of the stainless steel tube through the nozzle. During this phase, the same amount of liquid CO_2 flows through the nozzle as in cooling mode with the CO_2 bundle open. This can be seen by the constant flow rate at the nozzle after the bundle is shut off. As the liquid phase is flushed out of the stainless steel tube, it cannot expand in the line and cool the tube. This can be clearly seen in the temperature curve at both the inlet and outlet of the tube. The two temperatures are almost identical for evacuating with flushing. When the bundle is turned off, the tube has a temperature of about ϑ = 18 °C, because the cooled liquid CO_2 from the cooling section has flowed through it. The gaseous CO_2 for flushing does not pass through a cooling section and therefore has a temperature of approximately ϑ = 20.5 °C. The pipe heats up to about ϑ = 20 °C during flushing. When the gas phase is shut off, the residual liquid CO_2 from the supply line coming from the bundle can enter the stainless steel tube, expand and cool it down to about ϑ = 16 °C. This cooling is greater at the inlet than at the outlet due to expansion. If the shut-off valve for the liquid CO_2 supply line was installed directly in front of the T-piece in the direction of the stainless steel pipe, this final cooling could be avoided in a real installation on a milling machine.

4.3 Results for two-channel integration

The aim of the two-channel spindle integration test series is to investigate the filling and evacuation times and the characteristics of these processes. Three PEEK tubes with different diameters are considered. For comparability, data are also collected for the stainless steel tube.

The power of the heating plate can be determined at any time from the measured current at the heating plate and the specified voltage. The stainless steel tube and the largest PEEK tube (d_i = 1.00 mm) have the highest cooling power with approximately P = 125 W, see Fig. 10. The medium PEEK tube with d_i = 0.75 mm achieves approximately P = 110 W and the smallest tube with d_i = 0.50 mm approximately P = 95 W. The fact that the stainless steel tube with a significantly larger cross section achieves the same cooling capacity as the largest PEEK tube is due to the fact that from a cooling channel diameter of d_i = 1.00 mm, it is no longer the cross section of the cooling channel but the nozzle at the outlet of the test setup that is the limiting element for the CO_2 mass flow. A comparison of the flow rates shows that the largest PEEK tube actually has almost the same flow rate as the stainless steel tube. If the tube diameter is too small, the maximum available cooling capacity is severely limited due to the high CO_2 flow rate reduction. In addition, it is important to avoid increasing the tube diameter in direction to the process zone to prevent expansion due to pressure drop. A small supply line, e.g.

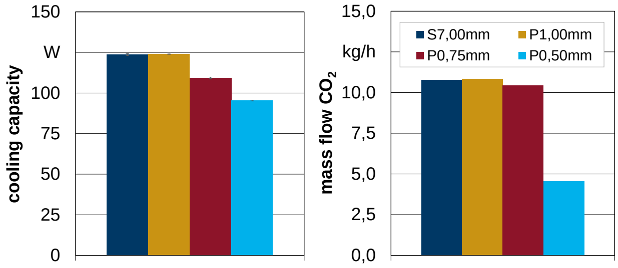

Fig. 10: Influence of spindle tubes on the cooling capacity.

d_i = 0.50 mm would therefore be unfavorable, especially for tools with multiple cutting edges and cooling channels. In the evaluation of the two-channel tests, the filling/evacuation times of the test series are first presented and compared. The times shown in Fig. 11 confirm the basic findings from the previous chapter on one-channel integration. Evacuation takes significantly longer than filling. Whether the test setup is oriented horizontally or vertically makes no difference for filling. For evacuation, based on the newly obtained data, it can be added that the vertical orientation only provides significant time savings for the stainless steel tube. For the PEEK tubes, there is no significant difference between vertical and horizontal emptying. In all processes and orientations, the PEEK tubes with d_i = 1.00 mm and d_i = 0.75 mm are the fastest. Although there is a very small difference between these two tubes, the d_i = 1.00 mm tube is slightly faster. The steel tube and the smallest PEEK tube have comparable filling and evacuation times for all processes. They are significantly slower than the two larger PEEK tubes. Strong cooling can be observed when emptying the stainless steel tube vertically to ϑ = 10 °C and horizontally to ϑ = -2 °C.

The stainless steel tube has a volume 49 times larger than the largest of the PEEK tubes. Filling this volume first creates a gas phase that must be pushed through the nozzle by the liquid phase. This is why the stainless steel tube has the longest filling time. When evacuating without flushing, not all of the liquid phase is pushed through the nozzle. Some of it remains in the tube, expands, and gradually flows out as a gas phase. This effect is particularly noticeable in a horizontal orientation where gravity does not assist the liquid phase to flow out. This means that the stainless steel pipe will take the longest to empty horizontally. At the same time, this is where the cooling effect is greatest.

The d_i = 0.50 mm PEEK tube has the smallest cross section resulting in lower mass flow rates and therefore requires more time to fill the volume between the PEEK tube and the outlet nozzle with liquid CO_2. For the line with d_i = 0.50 mm, the transition back to the supply line diameter with d_i = 1.7526 mm represents a significant increase in the cross section.

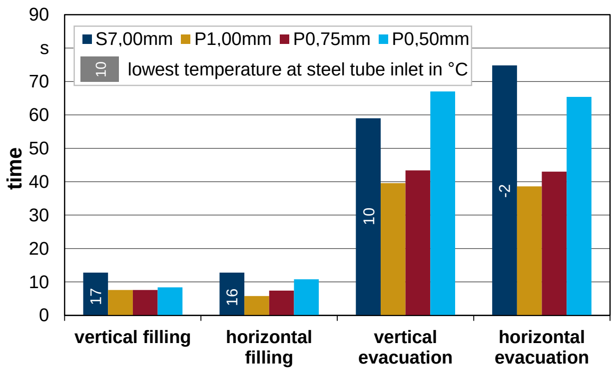

Fig. 11: Filling/evacuation times for two-channel integration.

The pressure drop downstream of the small PEEK tube ensures that the volume in direction to the nozzle is first filled with gas phase. As with the stainless steel tube, the gas phase is then flushed out by the liquid phase. This also takes longer with the $d_i = 0.50$ mm PEEK tube in a horizontal orientation than in a vertical orientation. The smallest PEEK tube therefore has the second longest filling times. If the bundle is turned off during evacuation of the spindle chamber, liquid CO_2 remains in the supply lines upstream of the cooling channel. This CO_2 gradually expands into the gas phase. The PEEK tube with $d_i = 0.50$ mm has a too small cross section to quickly remove the CO_2 mass flow through the nozzle. As a result, there is a continuous flow through the line until the remaining CO_2 is discharged from the supply line. This process is not supported by gravity as the limiting factor is the cross section of the PEEK tube. For this reason, it takes the same amount of time to empty the $d_i = 0.50$ mm PEEK tube in both orientations. In the vertical orientation, this tube takes the longest for evacuation, and in the horizontal orientation, where it takes the second longest. The PEEK pipes with $d_i = 0.75/1.00$ mm do not or only slightly have the problems associated with a very large or very small pipe cross section and are therefore faster in all processes.

5 SUMMARY

The results of this work show that the density of CO_2 can be reliably increased and density reductions can be prevented with a cooling section for supply line cooling. If the density is controlled by the cooling water, a cooling water temperature of $\vartheta_w = 10$ °C is recommended for this setup. For the one-channel concept, it is especially recommended to flush horizontally with the gaseous phase, as this shortens the evacuation time and prevents a large temperature drop. During filling, only a small temperature drop is prevented by pre-filling with gas phase, while filling times are doubled. The tests on the two-channel concept show that the shortest filling/evacuation times are achieved with the PEEK line di = 1.00 mm. However, the two-channel concept involves a very high level of modification to the machine spindle, and it must be possible to transfer the medium to the tool in a process-safe condition.

An alternative if the CO_2 is not evacuated through the nozzle or later through the tool is to evacuate it through a separate outlet. This can significantly reduce the evacuation time. Depending on the position of the outlet, flushing is recommended in order to remove the liquid phase and prevent a sharp drop in temperature in the spindle chamber.

6 ACKNOWLEDGMENTS

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