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Environmentally benign processing with CO_2 jets – A short story of a technology and its current and prospective applications

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Abstract
The development of CO_2 jet cutting technology began in 2009 with a simple prototype the Ruhr-University Bochum. Over the course of fifteen years, three DFG projects were initiated, yet the technology remains in a state of development, with a particular focus on industrial applications. In 2024, a continuously operated system, developed at Ruhr-University, has been connected to a six-axis robot at a partner institution. CO_2 jet cutting is similar to water jet cutting but offers dry and residue-free processing, thereby making it suitable for new applications. The cutting medium is compressed to a pressure of $p_0 \leq 300$ MPa, cooled to a temperature of -30 °C $\leq T_0 \leq 0$ °C, and depressurised through a nozzle to atmospheric pressure $p_a = 0.1$ MPa. Liquid CO_2 jets with lengths of $l_{jet} \leq 25$ mm are formed that can cut soft materials like plastics, metal foils, or textiles. In contrast to water jets, CO_2 jets result in a dry workpiece, thus obviating the necessity for energy-intensive drying procedures and enabling the processing of water-sensitive materials. CO_2 jet cutting avoids contamination issues associated with water jet cutting when processing harmful materials, as it precisely extracts toxic substances without requiring downstream treatment.

Carbon dioxide, CO_2, jet cutting

1 Introduction

The use of liquids as cutting media is established as industrial application since many years. The processing of materials with liquid CO_2 jets is a relatively new field of research, which has already progressed to the construction of a series of prototypes. Like water, the cutting medium CO_2 also offers the advantage of providing a tool that is always sharp. As CO_2, in contrast to water, is gaseous at atmospheric pressure p_a, it evaporates without leaving any residue after use. As a result, processed workpieces remain dry. The evaporation of CO_2 eliminates the necessity for downstream treatment or cleaning of the cutting medium or material. This enables the processing of water-sensitive and toxic materials [1].

A liquid, continuous and compact CO_2 jet must be generated for the cutting process. The jet should not be spread out into a spray, as this is not suitable for cutting. To generate these jets, compressed and tempered CO_2 is expanded through a nozzle. When the CO_2 is expanded from its liquid state to atmospheric pressure p_a, it changes into the thermodynamically stable two-phase state of solid and gas, as carbon dioxide has its triple point pressure at $p_{tr} = 0.518$ MPa. To obtain a liquid jet, it is necessary to delay this change of state. This allows the generation of a liquid jet at p_a which only evaporates after a certain jet length l_{jet}. This jet can then be used to process material [1].

Coherent jets are characterised by a continuous surface and a constant diameter over some distance downstream from the nozzle exit. Because of this structure, they have a high specific energy and thus lend themselves to jet cutting. Only if temperature T_0 and pressure p_0 upstream from the nozzle as well as the nozzle geometry are selected appropriately, the jet can be maintained in a liquid, possibly metastable state [1].

The theoretical limit for the existence of superheated liquids in the metastable state is given by the spinodal curve. When crossing the spinodal curve, a phase change is inevitable. Equations of state have been developed for the spinodal curve of CO_2 in the liquid-gas region, so that a comprehensive understanding of this region is available. In contrast, not much data is available regarding liquid CO_2 below the triple point pressure p_{tr}, in the solid-gas region, which presents a significant challenge in narrowing down the range of conditions relevant for CO_2 jet processing.

Whether a phase change is initiated in the metastable region depends on nucleation. The nucleation of gas bubbles can be homogeneous in a clean liquid, or heterogeneous on particles or wall-bound cavities. The nucleation rate J is the number of nuclei exceeding a critical size per volume and time. It can be seen as a measure of the likelihood of a phase change [2,3]. According to Blander and Katz [4], the homogeneous nucleation rate J_{hom} can be calculated from Equation (1). In this equation, n_L is the number of molecules per volume, B is a kinetic term determined by diffusion and fluctuation processes, W_{hom} is the work necessary for bubble formation, k_B is the Boltzmann constant, and T is the temperature of the fluid. The exponential character shows that the nucleation rate strongly depends on fluid temperature. To ensure a low nucleation rate and thereby a jet stable as possible, a low temperature has to be chosen.

$$J_{hom} = n_L \cdot B \cdot e^{\left(\frac{-W_{hom}}{k_B T}\right)} \qquad (1)$$

A lot of research has been carried out on the breakup mechanism of cold jets and the flow regimes as well as jet formation. The jet breakup is significantly influenced by the jet velocity v and the fluid properties [5].

According to Vahedi Tafreshi and Pourdeyhimi [6] and Lin and Reitz [7], the transitions between the flow regimes depend on the nozzle geometry and may be shifted to higher Reynolds numbers Re for flipped nozzle flow. Yet the common phenomena are observed for carbon dioxide jets.

In sharp-edge nozzles, the flow may separate from the wall at the nozzle entrance and constrict (Figure 1a), which results in increased velocity and decreased static pressure in the jet. If the pressure drops below the vapor pressure p_v, cavitation may occur and affect jet breakup (Figure 1b). If the constriction reaches the nozzle exit, ambient air enters the gap between the nozzle wall and the jet (Figure 1c). When this happens, the jet leaves the nozzle without wall contact and therefore without being affected by friction and cavitation. A column of liquid with a diameter smaller than the nozzle diameter $d_{jet} < d_N$ is formed. Such jets have a smooth, laminar and transparent appearance and are named constricted jets. The phenomenon of flow separation at the nozzle entrance is referred to as hydraulic flip and was first described by Bergwerk [8], and intensively investigated by Soteriou et al. [9]. Once hydraulic flip occurs, the breakup length increases significantly.

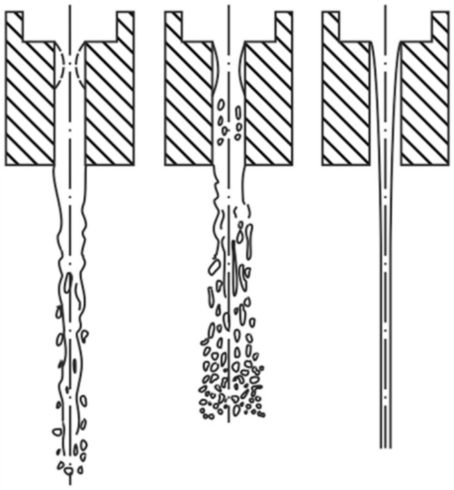

Figure 1. Jet appearances according to Hiroyasu et al. [10]

The authors believe that hydraulic flip plays an important role in generating liquid CO_2 jets, so a sharp-edge nozzle is used. In addition, the phenomenon of liquid jet formation can be correlated with pre-expansion pressure p_0, pre-expansion temperature T_0 and nozzle diameter d_N.

2 Methodology

2.1 Imaging

A high-speed camera Imager sCMOS from LaVision GmbH, Göttingen, Germany, used to take high resolution images of the jet. A light source, the object, and the camera are arranged along an optical axis. The light source is a double-pulse Nd:YAG laser with an intensity I = 145 mJ. The laser beam is expanded by a diffusor and illuminates a dye plate that acts as an incoherent background illumination. The light flash emitted has a wavelength of 574 nm ≤ l_w ≤ 580 nm and a pulse duration of t_p = 20 ns. Two different lenses allow magnifications between 1:3 and 12:1.

2.2 Cutting experiments

The cutting experiments are conducted on defined test samples to compare the cutting depth a_P and cutting quality of different experiments. The polyurethane materials utilised have been characterised with regard to their mechanical properties.

The samples were produced in a wedge shape with a tip angle α = 15° to calculate the cutting depth a_P of the CO_2 jet using trigonometric calculations, as seen in Figure 2.

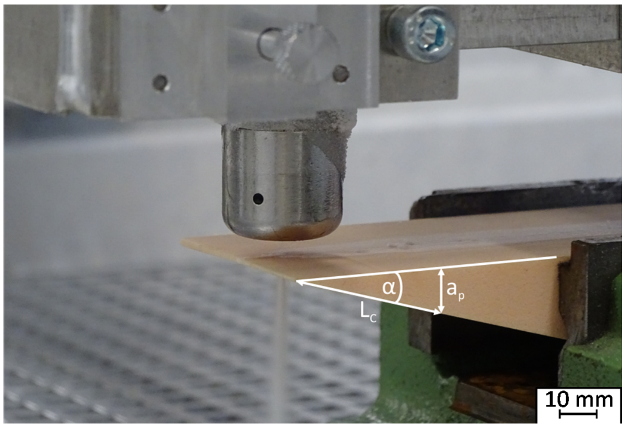

Figure 2. Cutting a polymer wedge with a CO_2 jet

This was achieved by measuring the length L_C and calculating the cutting depth a_P based on the known tip angle α using Equation (2).

$$a_P = L_C \cdot \sin \alpha \quad (2)$$

During the cutting experiments, the sample is fixed in a machine vice. The machine vice is affixed and adjusted on a X-Y table. This ensures that the sample cannot move during the experiments. The CO_2 jet is directed vertically onto the sample, and the cutting head is moved in a straight line. In this setup it is possible to set a defined distance between the nozzle and the sample, as well as the cutting speed v_c. The experiments were taken using nozzles of differing diameters, with values between 0.02 mm ≤ d_N ≤ 0.10 mm.

3 Experimental setups and results

3.1 Development of the technology

The gaseous state of CO_2 at atmospheric pressure p_a poses the challenge that the generation of cutting jets is only possible under certain conditions. In contrast to waterjet cutting, the process is not only pressure-dependent but also temperature-dependent.

First experiments were done at the Ruhr-University with a simple prototype built in 2009. The apparatus consisted of a single piston high-pressure pump 554.2320 from Nova Werke AG, Effretikon Switzerland, that was able to generate pressures of p_0 ≤ 300 MPa but with strong pulsation. Liquid CO_2 was taken from a riser pipe bottle, compressed, and cooled afterwards using a high-pressure heat exchanger connected to a water thermostat. For depressurisation a cutting nozzle Type III from ALLFI Group AG, Stans, Switzerland, was used, as commercially available for water jet cutting.

It quickly turned out that the generation of liquid jets with this equipment was barely possible. This was due on the one hand to the strong pulsation caused by the single-piston pump, and on the other hand to the limited cooling capacity. Therefore, a second apparatus has been built shortly after. This apparatus, as shown in Figure 3, was based on a pressure intensifier JCP 30 from, Jet Cut Power GmbH, Rotkreuz, Switzerland for water jet cutting, which was modified for CO_2.

Liquid carbon dioxide at an inlet pressure p_i = 20 MPa is taken from the laboratory supply system. The CO_2 flow is cooled twice, once before entering the pressure intensifier and once after compression.

Both heat exchangers used for this are operated with a thermostat Integral T 7000 from LAUDA DR. R. WOBSER GMBH & CO. KG, Lauda-Königshofen, Germany.

The process was designed to generate liquid, coherent CO_2 jets at pre-expansion pressures up to $p_0 \leq 350$ MPa. The liquid state was confirmed by images taken with a high-resolution photo system as described in section 2.1.

Figure 3. Water jet cutting system modified for the use with CO_2

It was found that to form liquid jets a pre-expansion temperature T_0 of the CO_2 close to the solidification line and a sharp-edged nozzle are needed. When a liquid jet is formed, its deformation and disintegration occur after approximately a jet length of $l_{jet} = 20$ mm downstream of the nozzle. The destabilising mechanisms that have been identified are the metastable state, the evaporation of the CO_2 at the jet surface and fluid mechanical instabilities [11].

Based on the findings by ENGELMEIER [11], a modular system for CO_2 jet cutting was developed. The previous components, which were partly components for water jet cutting, were replaced by ones specifically designed for CO_2. Additionally, the inflexible cutting head was mounted on an X-Y table using a flexible line. A newly designed cooling system positioned in front of the cutting head enabled the temperature control to be adapted such that sufficient cooling of the CO_2 could be achieved to produce liquid jets, even with longer pipe sections. This was realised with a third heat exchanger mounted on the cutting head, allowing the jet to be moved and enabling the processing of materials in two dimensions. A picture of this equipment is shown in Figure 4. This configuration provides the foundation for the industrial prototype currently under construction at the partner institute.

Figure 4. Current CO_2 jet cutting equipment at Ruhr-University

3.1 Experimental Results

With all equipment except for the first prototype, liquid carbon dioxide jets could be generated. Figure 5 shows high-speed photographs of CO_2 jets at different magnification rates. All jets were generated with a nozzle diameter of $d_N = 0.08$ mm.

The left column shows largely stable jets with only few instabilities in the form of singular bubble formation. The middle column shows jets with increasing instability, which are characterised by sectional evaporation and spray formation. The right column shows jets that are still liquid immediately after exiting the nozzle but disintegrate after a short jet length l_{jet}.

All jets have been formed under the same pre-expansion conditions and with a sharp-edge nozzle entrance. To further understand the mechanism of jet formation and to control jet stability is subject to current research.

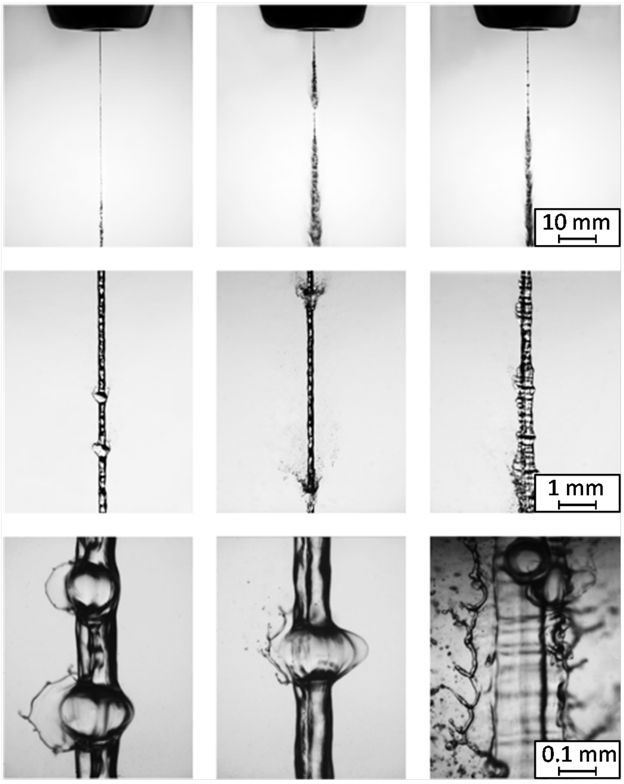

Figure 5. High-speed photographs of liquid CO_2 jets with jet instabilities increasing from left to right column [12]

Despite instability, liquid CO_2 jets allow the cutting of a variety of soft materials, including insulating materials, leather, and rubber. Harder materials, such as carbon fibre-reinforced plastic and glass fibre-reinforced plastic, have also been cut. The cutting experiments with CO_2 jets demonstrated that the processing of softer materials resulted in better cutting qualities than the processing of harder materials. The cutting depth calculations for the different materials indicated that a lower cutting speed v_c with a constant nozzle diameter d_N resulted in higher cutting depths a_P. This was evident for all nozzle diameters d_N and tested materials. It was found that an increase in nozzle diameter d_N resulted in a corresponding increase in cutting depth a_P. The best cutting performance was achieved with a nozzle diameter $d_N = 0.10$ mm. The jets generated with $d_N = 0.04$ mm still showed a cutting effect in soft materials, while jets with a nozzle diameter of $d_N = 0.02$ mm were not suitable for achieving recognizable cutting performance. This suggests a correlation between the mass flow rate $\dot{m}$ and the cutting depth a_P. A greater mass flow rate $\dot{m}$ was observed in experiments conducted with a larger nozzle diameter d_N. The higher mass flow rate $\dot{m}$ enables the jet to transfer a higher kinetic energy to the material.

It was observed that the geometry and structure of the cut are similar to those of waterjet cutting. However, the cutting kerf with CO_2 jet cutting is approximately 30 % smaller than with waterjet cutting.

4 Current research

The project partner is currently focused on intensive research aimed at further developing CO_2 jet technology into an automated and reliable process.

In addition to the requirements for automation, research is focusing on the factors influencing safety for people and the environment. Given that CO_2 acts as a gas that displaces breathing air, it is imperative that special safety precautions are taken to avoid potential hazards.

Another key research objective is the integration of this technology into a six-axis robot. This extends the application from 2D to 3D processing and enables the processing of large-volume and geometrically complex workpieces, thus expanding the application possibilities of CO_2 jet technology. The carbon dioxide pressure and temperature conditioning unit including cutting head is shown in Figure 6. The integration should result in more precise and efficient machining, thereby enhancing the technology's attractiveness for industrial applications. The long-term vision is to adapt CO_2 jet technology in such a way that it can be widely used in various industries in the future, while meeting the highest safety and efficiency standards.

To gain a deeper understanding of the formation of liquid CO_2 jets at atmospheric pressure p_a, the delayed phase change of CO_2 is currently being investigated at the Ruhr-University. This should assist to narrow down the process parameters for the cutting application, to find the optimum operating conditions.

The investigation of additional parameters led to the finding that liquid jets could also be generated at temperatures $T_0 \geq 0$ °C. The reduced tempering allows the system to be operated with less energy consumption. In addition to the studies by Engelmeier [11], nozzles with a diameter of $d_N \leq 0.08$ mm has recently been tested. It was found that as the nozzle diameter d_N is reduced, the pressure p_0 required to generate liquid CO_2 jets is also lower. The temperature range at which liquid jets can be observed has been found to increase in direct comparison to bigger nozzle diameters d_N.

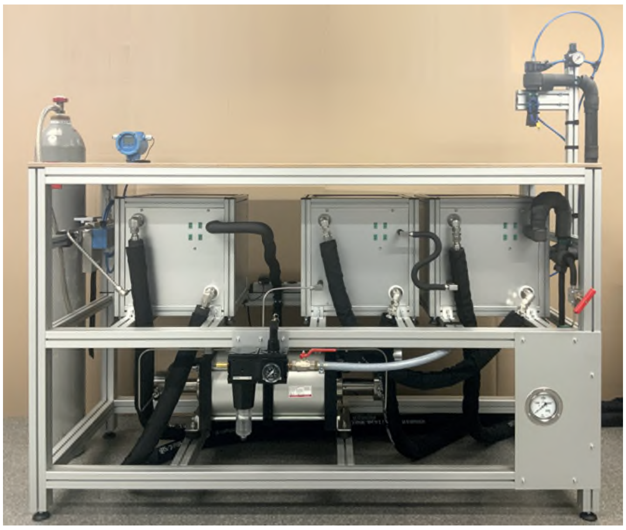

Figure 6. Newest CO_2 jet cutting equipment in Berlin developed in 2024

5 Summary and outlook

Over the time of development, a process was devised based on the initial prototype, which can generate liquid CO_2 jets for the processing of materials. The fundamental principle has been established and is currently being investigated and refined to adapt the process for a wider range of potential applications.

The outlook for CO_2 jet processing appears promising, with numerous potential advancements and applications on the horizon. This innovative method, which utilises a liquid CO_2 jet, offers a significant advantage over traditional water jet cutting by eliminating the issue of residual water on surfaces and the associated contamination.

In the textile industry, CO_2 jet cutting has the potential to offer a more efficient and cleaner alternative for fabric cutting, thereby reducing waste and improving precision. The utilisation of CO_2 jets has the potential to transform the manufacturing and maintenance processes within the aerospace industry. The capability to cut materials without leaving any residue is especially advantageous in this field, where precision and cleanliness are of paramount importance.

In conclusion, the potential for CO_2 jet technology to transform various industries is substantial, offering an environmentally benign, more precise alternative to conventional methods.

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