Cooling with Heat Pipes

Reduced Energy Consumption and Shorter Cycle Times due to Structurally Integrated Heat Pipe Mold Cores

In the injection molding of engineering plastics, mold temperature control consumes more than one third of the total energy input. Thus, energy for mold temperature control is a continuous major cost factor, adding up to around EUR 1.1 billion industry-wide in Germany alone in 2019. A novel technology offers the opportunity to reduce this amount – and eliminate hotspots.

The market for processing technical plastic parts is as large as it is lucrative. In Germany the production volume amounted to 3.3 million t in 2019, corresponding to a turnover of EUR 19.3 billion. Thus, after added value, a metric ton of engineering plastics was resold for an average of about EUR 6000, which is significantly higher than the average of EUR 4500 per ton for the entire plastics processing industry [1]. Although engineering plastics do not account for the largest share of the production volume, the figures show that these are components with special properties, which are sold at a price significantly above the average. However, a large proportion of the revenue generated has to be invested in the process. Regular energy expenditures in particular are increasingly becoming a cost driver.

With an average share of 37% of the total energy requirement (**Fig. 1**), mold temperature control is the main consumer [2]. Most products made of engineering plastics are subject to high mechanical requirements, accompanied by designed structural rigidity as well as a high degree of functional integration. It can therefore be assumed that most of these components are manufactured by injection molding. Assuming that some 90% are injection molded, this will require approx. 6 TWh of energy in Germany. The resulting costs amount to approx. EUR 1.1 billion [3].

The absolute consumption for the temperature control units can be calculated via the percentage share of heating power of 15% (**Fig. 1**). The energy requirement is determined based on the average enthalpy of the most common engineering plastics (ABS, SAN, PC, PMMA, ASA, PBT, POM and PA) and assuming that the plastic has to be heated from an average of 30 °C to a melt temperature of 275 °C [4].

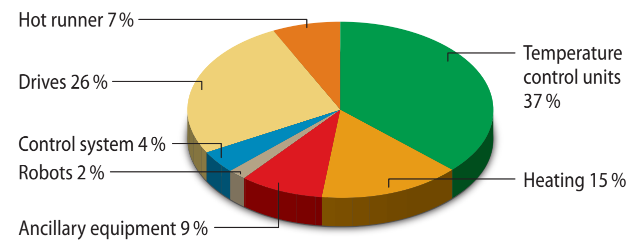

Fig. 1. The temperature control units have the highest energy share in the injection molding process Source: M. Schläger et al [2]; graphic: © Hanser

It is increasingly important to convert the required energy into the equivalent of CO_2 emissions. This results in a value of approx. 2.4 million t CO_2 [5], which corresponds to the energy consumption of approx. 2 million households with four persons each [6], the population of Hamburg, Germany [7], or over 250,000 flights between Düsseldorf, Germany, and Munich, Germany [8–10].

Why is this Cost-Intensive Amount of Energy Needed?

In the temperature control of injection molds, the most uniform possible temperature distribution in the cavity is decisive for quality and cycle time in most cases [11–13]. To achieve this, the temperature is usually adjusted by pumping water through the mold, heated with temperature control units, which may be energy-intensive. If the temperature control effort for complex article geometries is particularly high, several temperature control units are often used per mold side. A random sample in practice showed that at a utilization rate of 90% on 5.2 days per week, each temperature control unit is responsible for approx. EUR 5500 per year in energy costs. Although the figures may vary depending on the pump system, the heating capacity accounts for the majority of the energy consumption.

Conventional Temperature Control Has Disadvantages

Injection molding enables the production of complex molded parts, usually with the aid of equally complex mold designs. For many demanding applications, the conventional temperature control methods using water and copper (**Fig. 2, left**) in the mold [14–16] are often insufficient. Local heat accumulations (hotspots) occur, which are critical

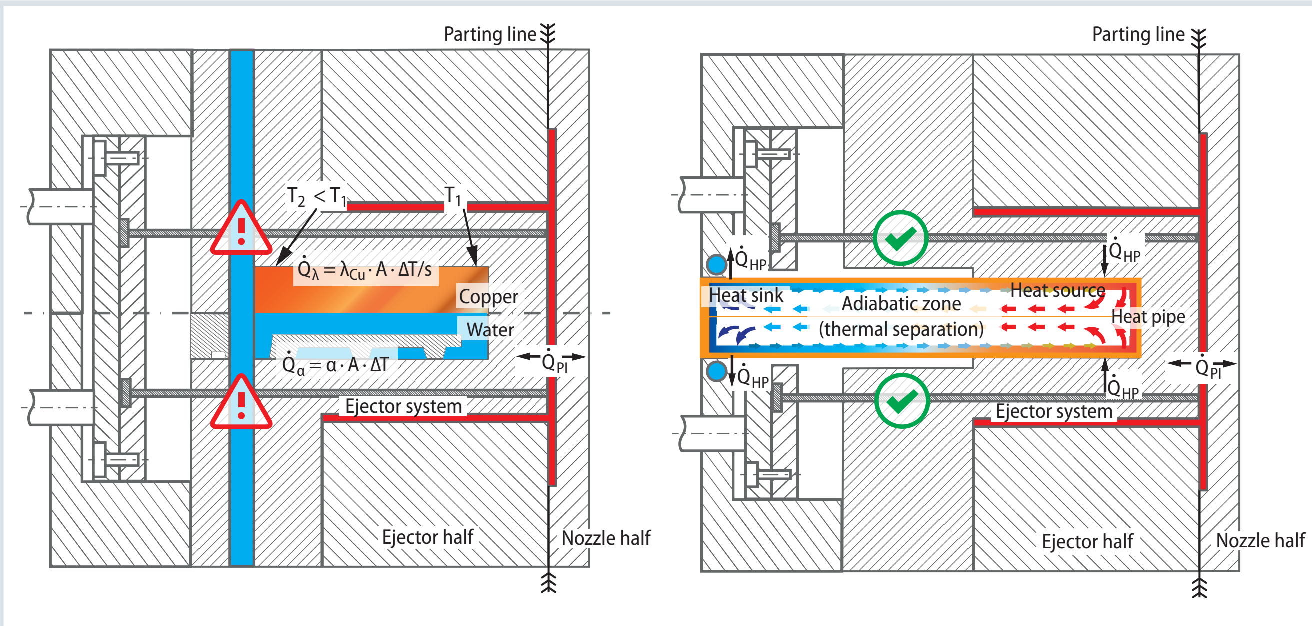

Fig. 2. Illustration of the temperature control methods copper and water (left) compared to the system with heat pipes (right; Pl = plastic)

Source: Bielefeld University of Applied Sciences; graphic: © Hanser

to the cycle and must be avoided. It is estimated that, for about 30% of all injection molds, a uniform temperature is not achieved at the cavity – with the consequence of extended cycle times.

There is a fundamental problem with narrow and long areas, where water is ineffective due to laminar flow behavior. Also susceptible to laminar flow are conformal temperature-control systems; in which additively manufactured or vacuum-brazed mold inserts, with small cooling channels, are used.

In addition, deposits with an insulating effect can form in the media-carrying channels, impeding the heat flow or, in extreme cases, leading to irreparable failure of the mold element. Therefore, it is advisable to invest in a water treatment system because maintenance intervals as well as incidental set-up processes are also cost-intensive and can lead to errors in reassembly.

Mold complexity is also caused by the temperature control channels, which run transverse to the ejectors. Often the customer specifies the positions of the ejectors without considering the temperature control – the design then becomes even more complex due to the lack of space.

Copper inserts are often located at critical areas. However, this system often requires greater effort for ancillary equipment. There is only a small temperature difference between the mold wall temperature and the temperature of the heat-removing water, which means there is very little heat flow. For effective heat transfer, the temperature must be lowered with a separate cooling channel circuit and temperature control unit, resulting in additional design effort. Refrigerant systems [17, 18] are another means of eliminating hotspots, but they are very costly.

How Can this Large Amount of Energy Be Reduced?

A research project at Bielefeld University of Applied Sciences, Germany, is pursuing the goal of using so-called heat pipe technology (**Fig. 2, right**) to save a large proportion of the energy and achieve shorter cycle times in the injection molding of technical plastic parts. The heat transfer rate of a heat pipe is many times higher than that of copper. Depending on the design of the heat sink and the arrangement of the cores, it can follow the route of the ejectors. This increases the design freedom and reduces the manufacturing effort. With this technology, it is possible to increase the lifetime of free-form cooling channels even in very confined areas. Since the system is hermetically sealed, no impurities can form even in very thin cooling channels, leading »

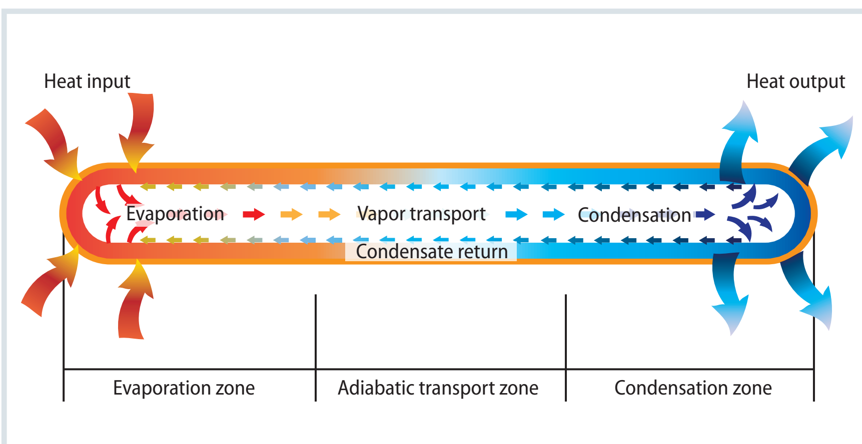

Fig. 3. Functional diagram of a heat pipe: vapor and condensate transport, phase transition areas and adiabatic zone Source: Bielefeld University of Applied Sciences; graphic: © Hanser

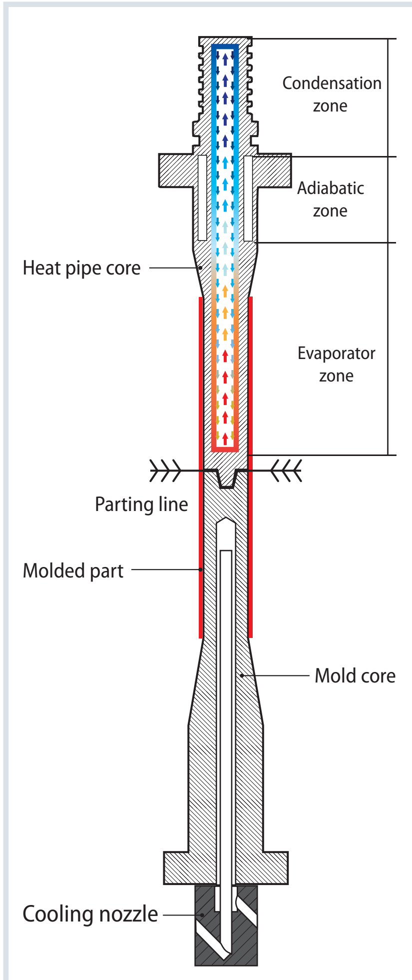

Fig. 4. Core system in longitudinal section: molded core cooling based on water (bottom) and structurally integrated heat pipe core (top) Source: Bielefeld University of Applied Sciences; graphic: © Hanser

to irreparable failure with conventional temperature control.

Heat pipes are sealed tubes with a negative pressure in their interior and are usually filled with a small amount of water (**Fig. 3**). The negative pressure causes the water to evaporate at temperatures as low as approx. 20 °C. The tubes are divided into three sections: the heat source, the heat sink and a thermal separation. At the heat source, heat energy is extracted from the mold as the water undergoes a phase transition from liquid to vapor – this results in cooling. The vapor is now the energy carrier and flows to the heat sink, where it condenses due to a lower ambient temperature. Thus, the heat energy is released to its surroundings. The water flows back to the heat source to evaporate again [19, 20].

The Mold Core Becomes a Hollow Body with Cooling Effect

The heat dissipation effect could be demonstrated in initial tests with the use of commercially available heat pipes [21, 22]. In addition, a precise simulation tool was developed [23–25]. Thermal simulation allows hotspots to be localized in the early development phase and the amount of heat energy to be dissipated can then be determined [26–28]. Heat-pipe mold cores offer the opportunity to eliminate hotspots where conventional methods are not effective. Thus, cooling time can be shortened.

Unlike in the past [15], Bielefeld University of Applied Sciences forms mold cores as structurally integrated heat pipes; so the core itself is the heat pipe. In principle, these are mold cores that are hollow inside and are evacuated and filled with a defined amount of pure water during manufacture. The advantages over conventional and assembled

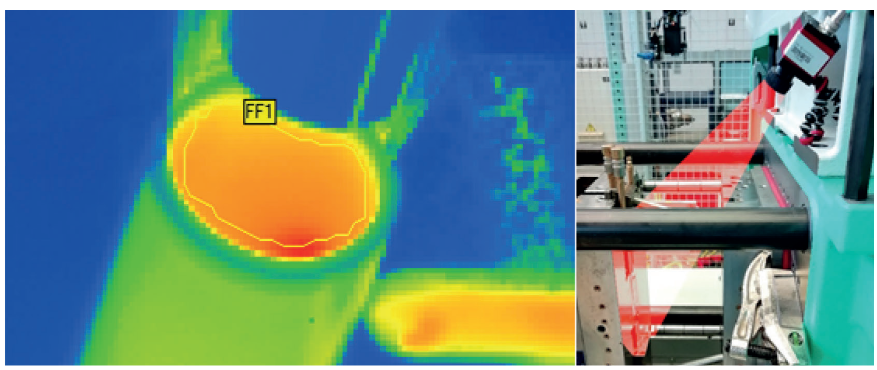

Fig. 5. Illustration of the thermal imaging camera with arrangement of the measuring area for the inside of the article (left) and view of the thermal imaging camera on the parting line (right) © Bielefeld University of Applied Sciences

Advantages at a Glance

The heat pipe is fundamentally characterized by a number of advantages:

- Energy saving potential
- Reduced need for ancillary equipment
- Chance of cycle time reduction
- Self-sufficient energy transport
- High design freedom
- Precise simulation

To-Dos until Series Production

There are still a few mandatory tasks before series production:

- Development of a rheology simulation with heat pipes as temperature control
- Consideration of further manufacturing processes
- Development of further structures (surface and cross-section) for optimized thermal behavior
- Formation of the adiabatic zone from ceramics with the aim of increasing the mechanical load capacity

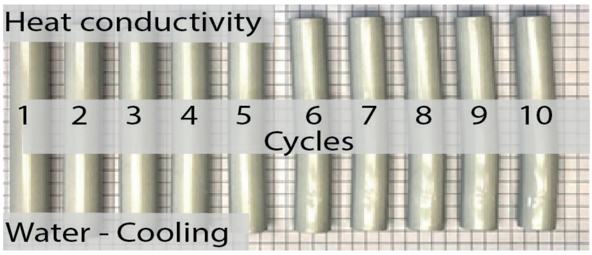

Fig. 6. Pure heat conduction in the mold core. Without the heat-dissipating effect the component already warped during the fifth cycle © Bielefeld University of Applied Sciences

heat pipes include defined and reproducible filling, better heat conduction from the cavity to the vapor chamber, and greater freedom of design.

A simple experimental mold can be used to compare water cooling with cooling by an additively manufactured, structurally integrated heat pipe [29, 30]. The article represents a sleeve, which is formed by two cores. The parting plane of the core system runs centrally from the article, creating symmetry and allowing a comparison of the two systems. The lower end of the sleeve-shaped component is temperature-controlled by a conventionally water-cooled core , while the upper part is designed as a structurally integrated heat pipe core (**Fig. 4**).

In the test series (**Table 1**), the mold was clamped on an Allrounder 370 E injection molding machine (manufacturer: Arburg). The temperatures were determined using a thermographic system (manufacturer: Infratec). This is an infrared camera of the type PIR uc 180 and the software Irbis 3. The graphical evaluation of the results is done with Excel. The mold is cooled by an energy-efficient temperature control unit with a speed-controlled pump. Based on the optical quality of the component, the limit of the process is determined with the shortest possible cycle.

The core temperature can be determined by thermographically recording the temperature on the inside of the article (**Fig. 5**) and calculating the contact temperature. The core temperature is steady-state at 91 °C for ABS and 60 °C for PP. The same article quality is found at both component ends, so that no differences can be seen in a direct comparison between the water-cooled and the component side cooled via the heat pipe core [31].

Proof that the heat pipe has a heat-dissipating effect could be demonstrated on the basis of pure heat conduction with water cooling. For this purpose, the vacuum in the heat pipe was dissolved and thus the core was cooled exclusively by the heat conduction of the steel itself. This showed that the component quality was not durable and that the component already warped on the side of the new core during the fifth cycle (**Fig. 6**), while no deformation occurred on the water-cooled side.

Saving Money and Cycle Time

With the novel approach of using a heat pipe as a mold element, the improvements in energy use and cycle time become directly apparent [32]. Proof of function can be provided in real operation. The cooling of a core is performed with cold water instead of a temperature control unit. If one wishes to set a different temperature on the core, there are basically three parameters available: the vacuum and the amount of liquid can be varied; and the heat transfer performance can be influenced by the temperature of the heat sink, e.g. by a cyclic water flow. In principle, heat-pipe pulsed temperature control is conceivable in this way.

In addition, the Bielefeld University of Applied Sciences is looking into convective temperature control of the heat sink in the future, so that the mold would be completely free of water and the pump and its power supply would also be eliminated. ■

	Total cycle time [s]	Cooling time [s]	Holding pressure [s]	Mass temperature [°C]	Water temperatur [°C]
ABS	7.3	2	1.4	230	16
PP	8	2.7	1.4	220	16

Table 1. Process values of temperature control Source: Bielefeld University of Applied Sciences

The Authors

Stephan Kartelmeyer, M.Sc., studied mechanical engineering at the Bielefeld University of Applied Sciences and the University of Paderborn, both in Germany. After working in industry for several years, he has been working on heat pipe temperature-controlled molds as a research assistant since 2016;
stephan.kartelmeyer@fh-bielefeld.de

Max-Vincent Hüttemann, B. Eng. has been working as a research assistant at FH-Bielefeld since 2017.

Prof. Dr.-Ing. Elmar Moritzer has been Professor of Plastics Technology at the KTP of the University of Paderborn since 2008.

Prof. Dr.-Ing. Christoph Jaroschek has been Professor of Plastics Processing at Bielefeld University of Applied Sciences since 1998.

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