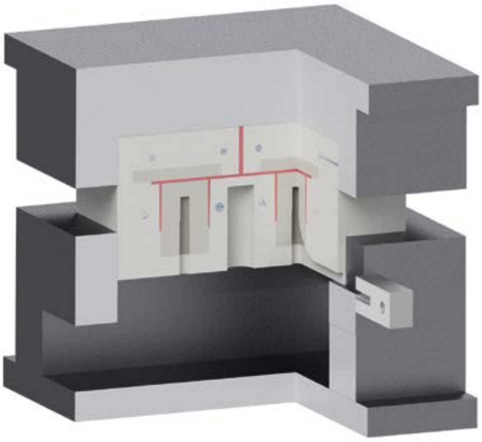

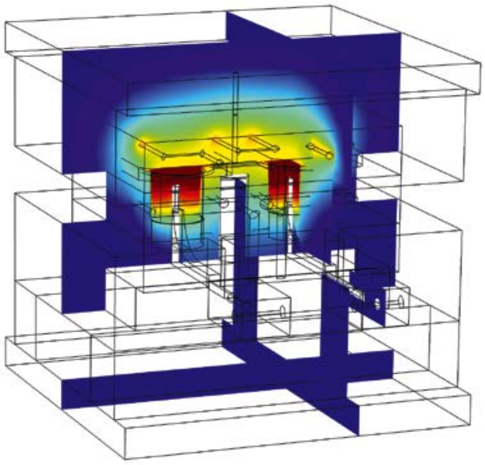

Heat pipes support rapid heat exchange. It is not absolutely essential to remove all the heat of the melt from the mold. It is also possible to define climatic zones in areas remote from cavities, into which some of the heat is directed (© Bielefeld University of Applied Sciences)

# "No Cool" Molds, Properly Simulated

## *Simulating Heat Flow in Injection Molds with Heat Pipes*

Bielefeld University of Applied Sciences has succeeded in developing an injection mold that does not require conventional liquid-based temperature control. Heat equalization is effected by means of heat pipes instead. Mold design and heat-pipe selection are based on the outcome of thermal simulations, which yield reliable results thanks to an unconventional approach.

Injection molding of polymers for technical applications requires temperatures in the mold cavities to be uniformly high. To this end, water or oil at a defined temperature is generally passed through the molds. This approach is not only highly energy-intensive but also requires the use of temperature-control devices. What is more, liquid-based temperature control has further disadvantages [1]. These include:

- Limited design freedom because the temperature-control channels run transversely to the ejector system;
- rust and contamination in the cooling channels;
- problematic heat transport, especially in the case of slim core geometries.

Water tends to flow laminarly in narrow-diameter areas, a fact which leads to a poorer heat transfer coefficient.

### *Ways to Cool Slim Cores*

There are different ways to cool slim cores. One is to install baffle plates, long slim cooling channels or cooling spirals in accordance with the diameter of the temperature-control channels. Where the temperature-control medium cannot flow properly in some areas, copper inserts are used. Another option for narrow geometries is to use air cooling [2].

There are design limits on the use of water-cooling systems and physical limits on the use of copper inserts. Heat transport is based on temperature difference. Without it, heat cannot flow along the copper insert. Then again, if the heat-removing element has different temperatures, different temperatures will also arise in the cavity. As a result, the temperature in the core will not be uniform. Copper inserts are therefore unsuitable for controlling uniform temperatures in long cores (**Fig. 1**).

The idea behind "no cool" molds is that conventional molds at temperatures above approx. 70 °C are heated predominantly with temperature-control media. The quantity of heat lost to the environment by convection and radiation frequently exceeds the thermal energy introduced via the melt, with the result that the external temperature control has to prevent cooling and tends to introduce rather than to dissipate heat, with the bulk of the mold initially having a uniform temperature.

Nonetheless, cyclical operation generates hotspots, especially in narrow core geometries where there is intense contact with the melt. There, more heat is released to the mold. If undesirable heating of these areas and thus longer cooling times are to be avoided, it is necessary to introduce temperature-control media at a lower temperature there. This temperature regulation, in turn, is dependent on the cycle time and requires additional external outlay, e.g., further temperature-control devices.

### *Problem Solved by Omitting Media-Based Temperature Control*

One alternative is to use heat pipes to bring about rapid thermal equalization

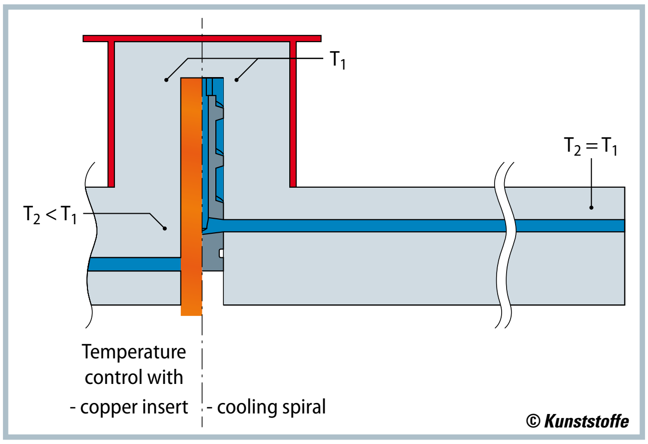


**Fig. 1.** Conventional temperature control of cores is based on the use of heat-conducting inserts or the flow of liquid media (source: Bielefeld University of Applied Sciences)

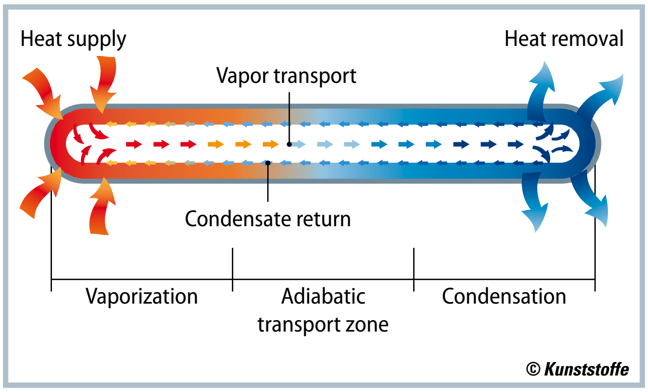


**Fig. 2.** Heat pipes exploit the temperature difference between heat source and heat sink (source: Bielefeld University of Applied Sciences)

within the mold. Such heat pipes are employed in space travel and in the cooling of electronic components, such as the CPUs of powerful computers and laptops, and increasingly in smartphones. The fact that they are used in smartphones highlights a prime advantage: heat pipes are very compact, fast-acting heat-exchangers.

They work autonomously, require no maintenance, transfer heat over long distances much faster than copper rods of equivalent dimensions and respond more dynamically to temperature changes than aluminum due to their low mass. Inside the heat pipe is a liquid which vaporizes at the warm side (heat source) and so removes the heat from the environment. The vapor flows across an adiabatic transport zone to the cold side (heat sink) where it condenses and releases heat to the environment. The condensed liquid returns to the warm side via internal capillary structures (**Figs. 2 and 3**). In the simplest case, the liquid is water, which vaporizes at about 5 °C under a suitable vacuum [3].

The heat transport system is reversible. The side of the heat pipe with the higher ambient temperature acts as the heat source in each case, while the other side is the heat sink. Thus, the warm side can be localized within the mold or can take the form of an external temperature-control element. Not only can heat thus be removed from the mold as required, but it can also be introduced, e. g., to heat the mold prior to startup (**Fig. 4**).

The no-cool injection mold (**Fig. 5**) developed at Bielefeld University of Applied Sciences, Germany, is modular in design and its temperature can be controlled conventionally with water as well as with heat pipes. This affords a way of making direct comparisons between the systems. It transpires that both systems perform equally well – the difference being that the disadvantages of conventional temperature control are eliminated.

## *Successful Simulation through the Use of Heat Pipe Characteristic Maps*

When it comes to the choice of suitable heat pipes and their positioning, multi-cyclical heat flow simulation highlights the critical zones where heat flow needs to be specifically improved [4]. That calls for a model capable of simulating the heat pipe. Three possible models are here:

- Define the heat pipe as a “specialty copper rod”,
- make full allowance for internal physical processes, and
- devise a black box scenario, with the real behavior represented by characteristic maps.

For the “specialty copper rod” model, a boundary condition imposed by the simulation is that the mass of the heat pipe be set to a very low value in order that this element itself may not absorb any heat. The thermal conduction is set to a value more than 1000 times that of copper. However, the lack of temperature dependence proves problematic because a functioning heat pipe requires a certain temperature difference at the two ends. In this model, the simulation would exaggerate the influence of a heat pipe and deliver incorrect results.

The “internal physical processes” model simulates vaporization and condensation as well as fluid transport via capillary forces, vapor transport and the resulting pressure profile of the heat pipe. Essential information is missing here in the case of commercial heat pipes as »

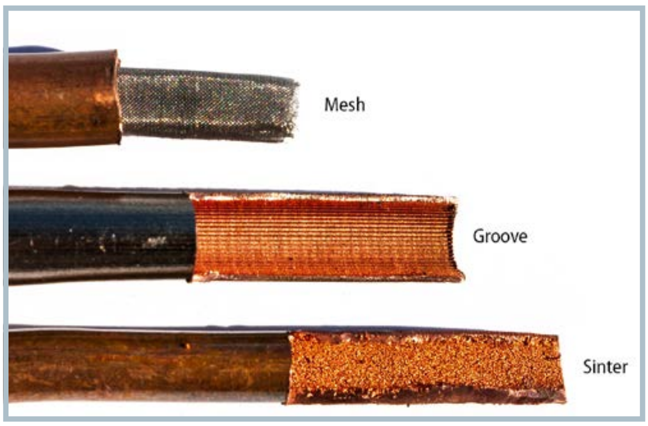


**Fig. 3.** The capillary effect can be generated by different internal structures in the heat pipes (© Bielefeld University of Applied Sciences)

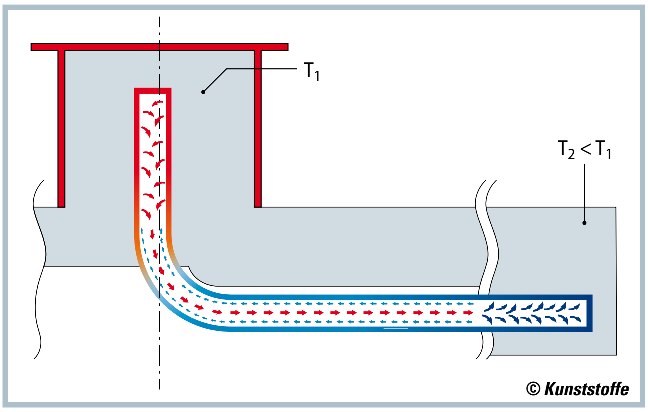


**Fig. 4.** Controlling the temperature of a core with a heat pipe (source: Bielefeld University of Applied Sciences)

regards the fluid, its mass, the prevailing vacuum and the geometry of the capillaries. The surface area for the evaporator and condensation area is larger by an unknown factor than the inner area of the circle due to the surface area of the capillaries. A simulation model would therefore have to adapt the results to real test data through the use of calibration factors. Furthermore, simulation of the model would take up too much CPU time.

The "black box" model takes the externally measurable effect of heat transfer into account. This model is not reliant on the availability of manufacturers' data. However, a characteristic map showing the transferable enthalpy as a function of local temperatures does need to be experimentally determined.

## *Characteristic Map Determination and In-House Qualification*

Heat pipes usually exhibit a peak in their heat transfer capacity. The boundary condition is the temperature difference between heat source and heat sink. Qualification of heat pipe capacity by means of characteristic maps is carried out with the aid of a purpose-built test rig (**Fig. 6**), which is capable of mapping a plethora of geometric criteria such as diameters, bending angles, radii and mounting points. Preliminary qualifications of comparable heat pipes available from various manufacturers (Quick-Cool, Wuppertal, and Hasco, Lüdenscheid, both Germany) under these boundary conditions reveal clear differences among them and make selection easy.

In the test rig, a heat pipe connects two copper blocks; these serve as heat source and heat sink and thus represent the mold and the temperature-control element. Various temperature differences are set via a variable starting temperature on the heat source. The heat pipe transfers thermal energy to the heat sink until there is no longer any substantial change in temperature. The temperatures are re-

**Fig. 5.** No-cool mold for a cap application; the heat pipes and removed core inserts are shown in the foreground (© Bielefeld University of Applied Sciences)

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## Service

### References & Digital Version

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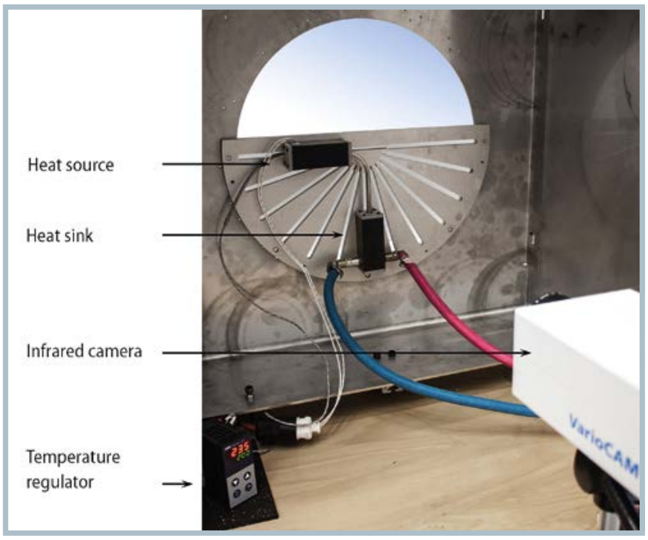


**Fig. 6.** Test rig for determining heat pipe characteristic maps. The temperatures at the two copper blocks are read with an infrared camera (© Bielefeld University of Applied Sciences)

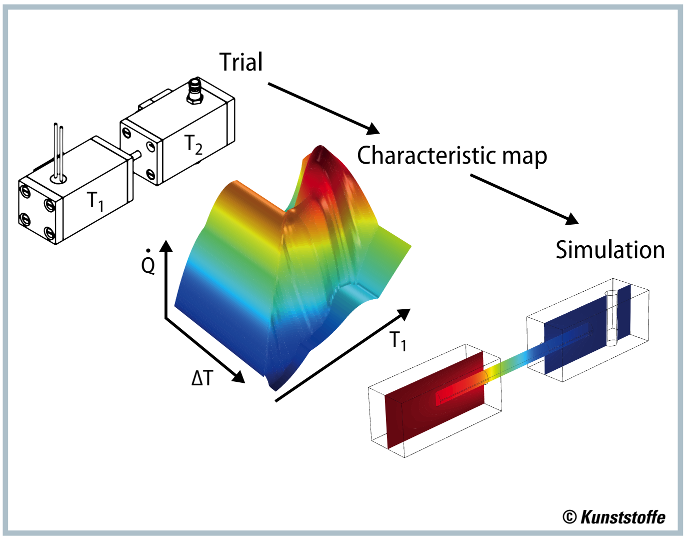


**Fig. 7.** The characteristic map of a heat pipe shows the transferable heat capacity as a function of local temperatures (source: Bielefeld University of Applied Sciences)

corded thermographically on the two copper blocks.

The heat transfer capacity of the heat pipe in watts can be determined via the internal energy of the copper blocks and the time required. In addition, software written for MathWorks Matlab processes the heat-loss readings automatically. The outcome is a three-dimensional characteristic map of the heat capacity transferred by the heat pipe (**Fig. 7**).

## *New Approach to Simulating Heat Flow in the Mold*

In a conventional simulation of mold temperature control, the heat quantity of the melt is directed into the mold across the surface of the cavity, and thence toward the cooling channel whose surface is assigned a fixed temperature (provided that heat transfer within the temperature-control medium is not calculated via CFD as well). Defined temperatures are not useful for heat pipe simulation as they are characterized by the heat transfer capacity. In the simulation, a heat transfer capacity from the characteristic map is assigned to the contact surface between the heat pipe and the mold. The other end of the heat pipe is assigned the same capacity value, but of opposite algebraic sign.

Since the present boundary conditions are variable, the characteristic map returns the right heat flow for the surface. By integration of the generated characteristic maps through mathematical interpolation, the heat transfer properties of the heat pipes and thus the temperature control can be adjusted exactly.

Comsol Multiphysics simulation software proved to be very useful. This software features an option to read in the characteristic maps and to parameterize the physical properties in the model itself. The polymer input is modeled as a cyclical event which heats the cavity to the melt temperature as a function of the cycle time. The temperatures in the mold (heat source and heat sink) are recorded via probes in the simulation model. The temperatures of the probes determine the capacity data from the characteristic diagram.

Due allowance having been made for detailed material values for determining the heat energy introduced and other factors, such as convective losses, radiation, the influence of injection pressure and clamping force or heat conduction at the part transition, a precise simulation of the heat flow in the mold can be generated.

Aside from facilitating a comparison of temperature-control systems, the no-cool mold is used to validate the thermal simulation in the mold. Several successive simulation cycles were found to differ by 2 °C from the temperature readings during mold proving. In practice, the temperatures of the cavity were recorded by means of a thermal imaging camera with the mold open. To ensure high measuring accuracy, emission values from the surface were taken into account and for the measurement the thermal radiation of the heat reflected from the environment was subtracted from the calculation.

The results of the simulation can be evaluated by the simulation software from many different aspects and not just with a view to optimizing the temperature-control concept. For example, they can establish when a quasi-steady state is reached in the mold. The simulation is highly accurate, but still time-intensive. It is however possible to simulate scenarios for standardized cases and to develop guidelines that will enable mold builders to be selective in their choice and positioning of the heat pipes.

## *Outlook*

The studies showed that heat pipes make for a suitable temperature-control solution, especially for narrow mold areas, and can now also be used for simulations. Findings obtained from heat simulations can be designed into a temperature-control concept that meets requirements. Here, the method provides a precise thermal representation of the mold through the heat-pipe characteristic maps. Ideas for potential applications are currently leaning towards temporarily storing the excess heat energy from critical areas in the mold or directing it into areas where energy is needed, e.g. to avoid visible welds. ■