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COOLING OF ELECTRIC MACHINES BY MULTI-PHASE SYSTEMS

Abstract: A high potential for increase the power density and the efficiency of electrical machines consists in a improved cooling. A new implementation approach is in the pouring of the electric components into a medium, which guarantees a better heat emission to the case in a combined manner with a new cooling concept by utilization of change its phase, with that maximum loads can be absorbed thermally. At a realistic experimental model on the basis of a 3 kW induction motor of assembly line production the use of the different physical effects during heat storage was examined for the suitability for an electrical machine, when this equipped with chambers with technical paraffin were.
There are represented the experimental investigations at a modified induction motor and with its result the potential of this development. Measurement and computations show the better cooling of the solid one and both the liquefied material compared to air circulation. On the other hand, the effect of the fusion heat is still insufficient because of bad heat conduction qualities of PCM material for the practical application. By means of thermal FEM simulations the experiments are supported and possibilities for new materials examined.

1. INTRODUCTION

Electrical motors belong to the most common drives in industry. Their field is only then limited, if the required power density or the availability of electric energy make necessary or useful the hydraulic one or combustion engines its. However, the enhanced effort of renewable energy leads to an intensified turn for alternative drive concepts in the mobile field. During adaptation to direct drives, the thermal decoupling is dropped often from motor and process and the necessity exists of an intense motor cooling.
Withal the trend in the lower and middle performance range goes clearly for the design of the permanently excited synchronous motor. A further trend is the design of the winding as so called teeth coil technique which allows the construction of machines with shorter and bulk winding overhangs. At this principle potting the winding overhangs becomes interesting partial to its protection and for better heat conduction and is already practised occasionally.
A further aspect is conflation of electrical motor and electronics. At the integral motor for example, an induction motor and an inverter are integrated into a spatial unit. Equally at the power electronics there are efforts for potting the power semiconductor. Due to the spatial integration in a single cooling system, there are new solutions by taking advantage of innovative cooling concepts such as the use of changes in the aggregate state, which are apt to combine the use of different thermal time constants of motor and electronics.
However, the integration of power electronics and the cooling medium causes a serious interference in the structure of conventional drives, which should be balanced with the potential benefits (Fig. 1).

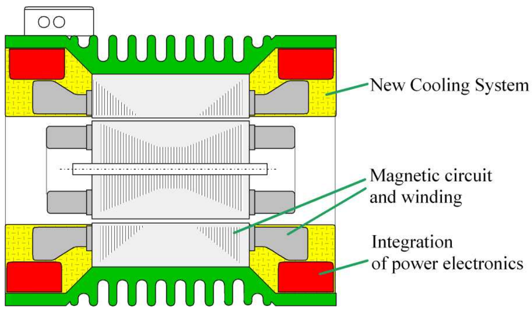

Fig. 1. New cooling concept

This concept is not exploited in electric drive technology so far. In contrast, in other technical fields such as the architectural and medical technology utilization of both the sensitive and the latent heat storage is common technologically-industrially.

2. PHYSICAL BASIS

Three effects supply the physical background for the new cooling system. These concern the effect of a better heat conduction of instead of air, the heat transfer within the melted medium and the especially here essential and new effect of energy storage by phase change.

Thermal conductivity $\dot{Q}$ describes the heat flow in the interior of solids and not moving liquids and gases, and with the thickness d and the cross section A for a temperature gradient in the direction of heat flow with the thermal conductivity λ

$$\dot{Q} = \frac{\lambda}{d} \cdot A \cdot (T_1 - T_2) \qquad (1)$$

Convection is the transportation of heat energy when the heat is transferred to a gas or a liquid and is advanced by the current it. The heat flow is with the heat transfer coefficient α

$$\dot{Q} = \alpha \cdot A \cdot (T_1 - T_2) \qquad (2)$$

The convection has the decisive role to play during heat emission by the surface of the machine to the environment as well as by a connected cooling circuit.

Heat emission by radiation is compared to convection of smaller importance at surface ventilated electrical machines.

Heat storage in materials will take the form of sensible or latent heat. As sensitive (sensible) heat is called the amount of heat ΔQ that results in energy supply to a temperature increase with the specific heat capacity c_m

$$\Delta Q = m \cdot c_m \cdot \Delta T \qquad (3)$$

As latent heat (not sensible, because it leads to no increase in temperature) is called the amount of heat that is absorbed or released during a phase change with the specific heat of fusion *q*.

$$Q_S = q \cdot m \qquad (4)$$

Heat storage will describe too with the term of enthalpy H_m used in simulation, which comes from thermodynamics with that the inner heat contents of a system is described.

3. PHASE CHANGE MATERIALS

3.1 Material requirements

Phase change materials (PCM) use the enthalpy change during the phase transition for storage of heat. Thereby it is first advantageous to achieve in a small temperature range relatively high storage densities, and secondly, it is possible to equalize variations in temperature and to prevent temperature peaks. The essential requirements for PCM materials vary depending on the application [1]. They are of physical (proper temperature of the phase transition, high melting enthalpy, heat capacity, thermal conductivity; reproducible phase transition, low undercooling), technical (low vapour pressure, volume change, corrosiveness; chemical and physical stability) and market type (low price, toxicological safety, handling / processing). The most important feature is the maximum storage density. The low thermal conductivity is one reason that these materials have not yet succeeded to a greater extent.

3.2 Common PCM products

Known PCM (eutectic salt-water solutions, paraffins, salt hydrates) and new products (mixtures, sugar alcohols) are shown in Fig. 2 with its energy density and melting temperature.

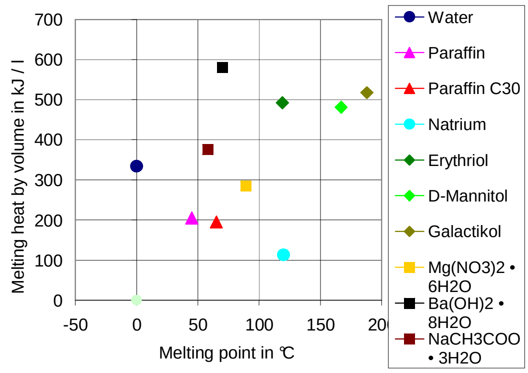

Fig. 2. Survey of selected PCM materials

Eutectic salt-water solutions because of its melting temperature < 0 °C are preferably used for the cold storage.

Paraffin have a melting temperature up to 150 C and are therefore very variable in use. Their application is technically simple. They show no separation, are cycle stable, chemically inert and not toxic, in particular, they do not cause corrosion of metals.

Salt hydrates (example: sodium acetate trihydrate NaCH3COO•3H2O) also have long been known. They have a relatively high melting enthalpy. Also, due to their low price they are industrially used mainly to a greater extent in the field of cold storage. A disadvantage is the tendency to separation during melting.

New PCM are eutectic mixtures of salt hydrates (example: magnesium nitrate hexahydrate Mg(NO3)•26H2O). They have compared to pure products no phase separation and high cycle stability. Due to the multi-component, there is a higher rate of melting temperatures. The potential is particularly high on melting enthalpy [2].

Sugar alcohols (examples erythriol and mannitol) as reaction products of carbohydrates are organic in nature and constitute a particularly interesting group among the new PCM [3]. They show no separation, no chemical corrosion of metals and the melting points are located in the range of permissible temperature rise of electrical components, both conventional electric machines and power electronics.

Further developments of PCM materials deal firstly with the encapsulation. Secondly, there are successful attempts to contribute to better thermal conduction by composite materials (factor of 100 with porous graphite matrix at 85% volume rate of PCM [1]).

3.3 PCM products for electro techniques

The suitability of PCM for electrical engineering must be differentiated by its constructive solution. For direct cooling, salt hydrates and salt water solutions leave because of their corrosive qualities. The salt hydrates favoured for medicine engineering fail equally because of compartmentalization and the low temperature level. The eutectic compounds of salting hydrates come into consideration in an enclosed form because of their high melting enthalpy. Sugar alcohols appear extremely attractive for electrotechnical plants because of their relatively high melting enthalpy, chemical neutrality and temperature range. However, their production is only biologically feasible and not available in required quantities.

For these tests has resorted to the traditional paraffin on an industrial basis. Fig. 3 shows its storage capacity in comparison.

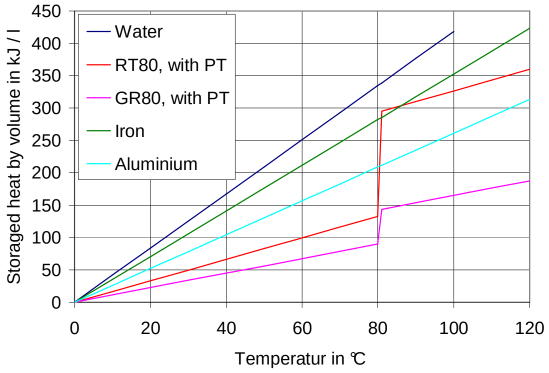

Fig. 3. Stored amount of heat for RT80 and GR80 with phase transition (PT) compared to other materials without PT, by volume

There was investigated pure paraffin RT80 and granules GR80 [4] with a melting temperature of 81 C. The granules GR80 were not used because of its poor thermal conductivity. The temperature range for electrical components in fact too low, however should be the basic results tends to be generalized to other materials.

4. MEASUREMENT RESULTS

4.1 Model construction

For arrangement of the cooling system were chosen two structurally identical standard engines on the basis of 3 kW induction motors with squirrel cage from the series production of the VEM motors Thurm GmbH of the series KL0R 90 L 2. With it are guaranteed same electro-magnetic features of the standard machine **ASM** and the machine with a new cooling system **ASMmK**. These are special designs that are extended axially in both directions to accommodate the new cooling system; with additional space on the NS (non-driving side) compared to the DS (driving side) for the placement of the electronics dummy.

Before implementation of the cooling system, the replica of an electronic assembly was inserted into the motor on the NS. This is built up from six resistances which are mounted on a cooling element (Fig. 4). The connections are led by a boring in the case outwards. Thus each of the six resistances is similar to a power switch like MOSFET or IGBT of an inverter.

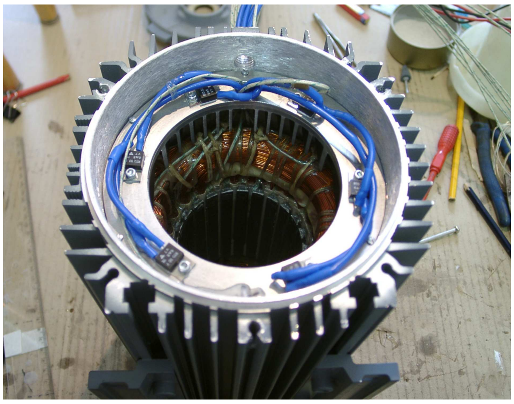

Fig. 4. Motor with electronic dummy, visible: Cooling element

The container of paraffin must include the winding overhang on the DS and on the NS additional an electronic dummy. The seal is to in this case be guaranteed to the container wall and the stator internal diameter. The entire stator internal core is sealed with resin to the air gap. The two paraffin containers remain as a result in contact on the slots and the stator core.

For the containers, a corpus of fibreglass texture was formed, impregnated with resin, thermally cured and inserted into the motor. This is liquid dense and locates the PCM to the end shields as well as the rotor. Fingering kind projections on the case fix this in the stator slots. The PCM lies to the motor housing inner surface, the front ends of the stator up to the slots and the entire stator winding.

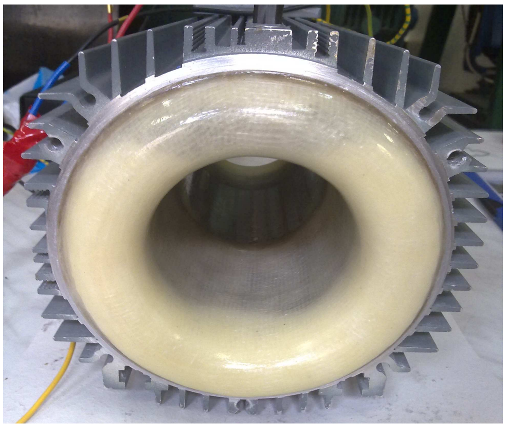

Fig. 5. 5th motor with Paraffin-filled container, melted in the upper part

The paraffin is a dry fine-grained granular material however, proved to be filling in the liquid state in the preheated stator as favourable. Due to the connection of the containers on the stator slots, as well as welding and laminated core, the one-sided filling sufficed. The volume expansion is ensured by the filling tube and the terminal board.

4.2 Test of the prototypes

On the test bench the ASM was connected with a converter-controlled load machine via a torque-measuring shaft (Fig. 8).

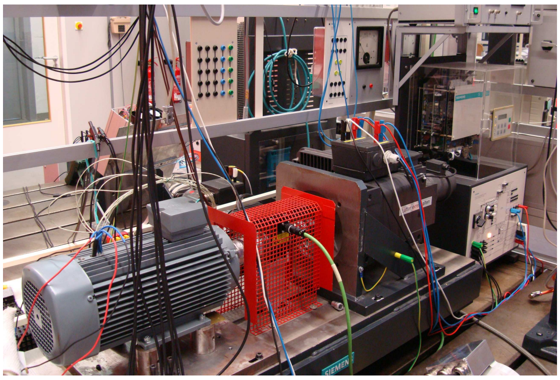

Fig. 6: Experimental setup, to the left ASMmK

For all measurements, greater heat dissipation was found by the improved thermal conductivity in the motor compartment. This leads to smaller temperatures while the heating process and in the stationary state. Direct at the winding overhang could be measured a final heating smaller up to 16% while 1,25-times rated power (Fig. 7).

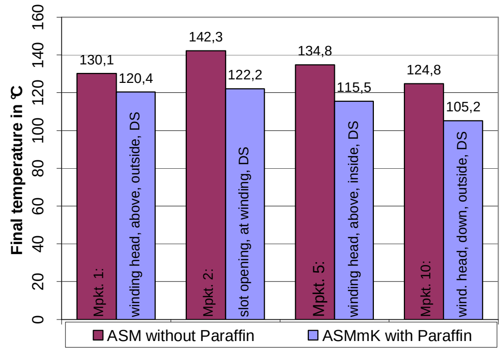

Fig. 7. Comparison final warming of the ASM and ASMmK with new cooling system

Thus the expected results for solid PCM have been achieved with the positive effect on motor efficiency, overload capability and expected life of the winding. After exceeding the melting point, it comes to a stronger heat dissipation and equalization of temperature by convection in fluid paraffin. It results a temperature difference between upper and lower part of the engine with increasing temperature in fluid paraffin. With increasing heating and/or liquefaction of paraffin, convection also occurs in this. An assimilation of the temperatures occurs with it at the winding overhang.

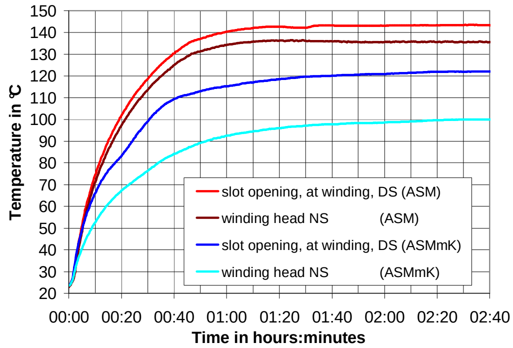

Fig. 8. Heating processes of the ASM and of the ASMmK with new cooling system

The important effect of a delay in the warming phase change by latent heat storage is evident in the temperature gradient measurements, but still too low. In ASMmK large thermal time constants occur in comparison to the standard machine. Because of the poor thermal conductivity of paraffin as an uneven and incomplete melting occurs particularly in the axial direction. These results were favoured that all demands were considered for a great effectiveness of the cooling system in the construction. The paraffin is above all available in all relevant places and even intersperses the winding.

5. SIMULATION BY ANSYS

For an accurate depiction of the material properties user-defined functions are necessary in order to form temperature-dependent thermal conductivity after melting. The mass related enthalpy H_m is interpreted as integral over the temperature dependent heat capacity in consideration of the phase transitions. With the Gauss-distribution is formed a closed function.

$$H_m(T) = \int_{T_0}^{T_e} c_m dT + \int_{T_0}^{T_e} \frac{q_m}{\sigma \cdot \sqrt{2\pi}} \cdot e^{-\frac{1}{2}\cdot\left(\frac{T-T_s}{\sigma}\right)^2} dT$$

(5) with σ: Standard deviation in Kelvin, T_S: melting temperature

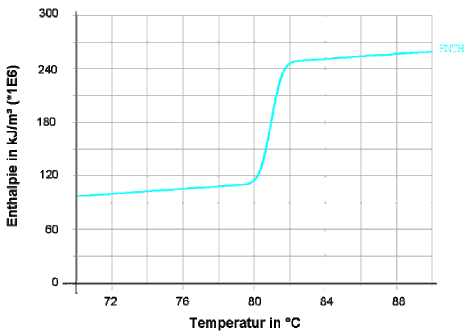

Fig. 9. Enthalpy curve for paraffin (detail)

By 3D modelling in ANSYS stationary and transient thermal analysis to determine the temperature and heat flux density is possible in the entire simulation model. For comparison with the experiments temperature samples were placed at the points of measurement points. The more problematic assignment of convection and heat transfer coefficients was made in coordination with the measurements (Fig. 9).

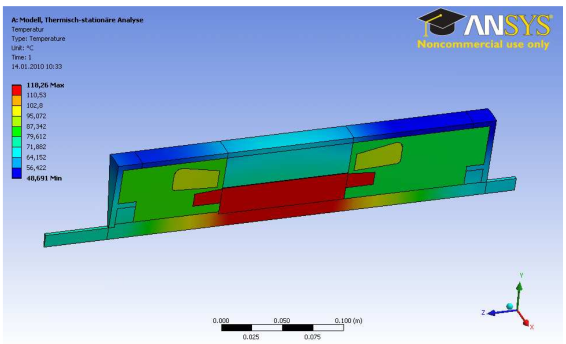

Fig. 9. Temperatures in the simulation model similar to the ASM at rated power

The simulation model also forms the basis for the recalculation of the new cooling system for any load conditions. The PCM is modelled in the airspace of the stator. Unlike conventional structures a temperature gradient in the paraffin is formed in the axial direction (Fig. 10).

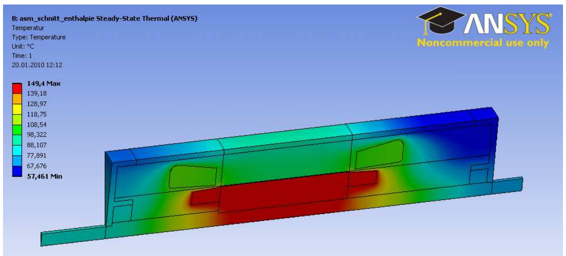

Fig. 10. Temperature distribution in the model of the ASMmK with new cooling system

The model also allows simulation of the transient calculations, the melting behaviour of the PCM material, and the simulation of cyclic load. It was found as in the experimental studies the problem of heat distribution due to the poor thermal conductivity of the paraffin. With real material data only a small delay of the temperature rise in the winding occurs (Fig. 11), while the slow melting of the remaining volume is not technically relevant.

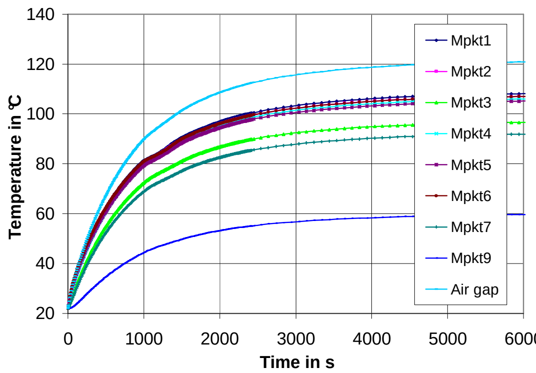

Fig. 11. Heating process of the ASMmK with paraffin in simulation

These statements coincide with the measurements on the model motor. For statements to actual the overload capability of the motor or to the mean temperature during at cyclic loading the solidification phase is to consider. This may require at PCM with strong supercooling a longer recovery period. The simulation shows a bubble with liquid paraffin which remains inside the container (Fig. 12).

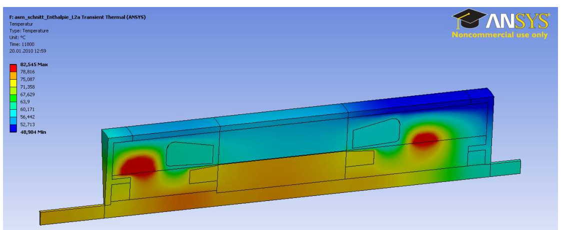

Fig. 12. Temperature distribution in the model during the cooling phase

With the simulation models the heat-storing effect of any PCM is predictable. By means of a substantially increased thermal conductivity at same melting enthalpy the rapid and complete melting of the entire storage volume is achieved (Fig. 13).

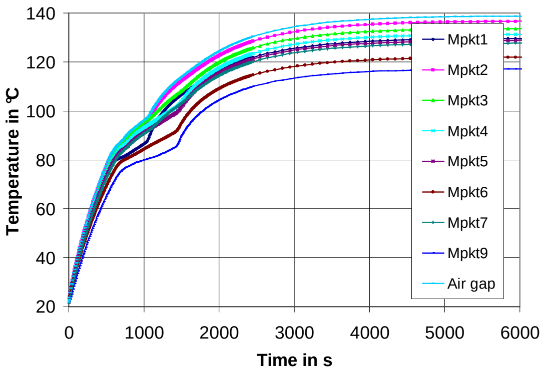

Fig. 13. Course with increased conductivity of the PCM, $\lambda = 200\,W/m/K$

The standard induction motor can be described with the conventional temperature models by a e-function approximation. There are valid a heating and cooling time constant, the final value of the warming is determined by the performance of the heat source. The arrangement with paraffin, however, is by simple mathematical functions of engineering skills no longer writable.

6. CONCLUSIONS

The investigations on the model of an asynchronous motor have shown that the transfer of PCM in direct contact with windings of electrical machines is possible and can improve the loss transfer and further data of the machine. With the thermal FEM simulation models in ANSYS, the possibility could be managed to be able continuing investigation for further materials or structures without extensive experimental studies.

For the effect of the utilization of the heat of fusion, the poor thermal conductivity of the PCM hinders a rapid breakthrough in technology. Further work should therefore focus on materials research, and less with the aim of finding a medium with higher storage density that is suitable for the conditions of electrical configurations than rather to achieve better utilization of the available volume by better thermal conductivity.

The selection, arrangement and the amount of PCM material must be matched to the engine and the respective loading, just as the the melting point with the limit temperature of the windings. One possible application of the principle is given in the equipment of a motor with the new cooling system instead of buying a more powerful drive.

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