THE UNUSUAL WATER COOLING APPLIED ON SMALL ASYNCHRONOUS MOTOR

Michal Sikora*, Radek Vlach*, Petr Navrátil*

This paper is concerned with unconventional water cooling that is primarily intended for medium-power synchronous generators. A configuration of the proposed cooling was briefly described here. A way how to estimate the main thermal resistance related to the new water cooling system was presented here. A small induction motor was selected for practical verification of the proposed cooling concept. Measurements executed on this motor showed correctness of water cooling parameters design and superiority of this cooling method comparing to another traditional methods of cooling.

Keywords: *water cooling, pipe, asynchronous motor, measurement, FEA, CFD simulation*

1. Introduction

Today's modern electric machines achieve a high power-to-dimension ratio. As a consequence of this, we need a highly effective cooling and ventilating system which can ensure sufficient heat removal from the machine inside. There are several ways how to cool electric machines; an air cooling is often used for heat removal from low or medium-power electric machines. Unfortunately, internal surfaces inside the machine, which can serve for heat removal, have usually limited area and heat-transfer coefficients on these surfaces are relatively small.

Substantial improvement can be achieved by different cooling method, for example by direct water cooling. The water cooling is able to ensure relatively low temperatures of a stator, as is stated in [1], [2], [3] or [4]. The water-cooled machines do not need a big external heat exchanger (air-water) which is usually installed on top of medium-power synchronous generators cooled by air. Therefore, the water-cooled machines can be significantly smaller than air-cooled variants.

The advantages of water cooling can be summarized as following:

- Stator radial canals are not necessary. The stator can by shorter.
- The water cooling is highly effective due to high specific heat capacity of water and high heat-transfer coefficients.
- We can achieve better power-to-dimension ratio of the machine.
- Low noise level.

There are a lot of different variants and configurations of the direct water cooling. Very effective water cooling is usually used for the biggest generators – cooling effect is ensured by a flow of water through the hollow conductors ([5], [6]). Smaller machines are usually

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cooled by another way; lot of information resources (such as [1], [2], [3], [7] or [8]) describe a water jacket built into a machine housing. The advantage of this type of water cooling is a large wetted surface.

A heatsink that is placed between two parts of a stator core can be used for cooling of axial-flux permanent magnet machines, as is presented in [9]. This realization is very effective, but unsuitable for application on conventional (radial-flux) machines. There is also an effort to integrate the water cooling directly into the stator slots, as is stated in [10].

An interesting style of the water cooling is described in [11]. The cooling of a special permanent magnets motor consists in installation of thin cooling pipes around the stator packet. A high-volume water jacket is not necessary here, but a thermal resistance between stator packet and pipes has to be sufficiently small. It can be achieved by glue with appropriate heat conduction. We decided to engage in a similar (but slightly different) style of the water cooling, which we design primarily for the medium-power synchronous generators.

2. Proposed water cooling

The scheme of the designed water cooling is presented in Fig. 1. A majority of losses is generated in the stator. Therefore, water can directly remove this heat from the stator through thin pipes walls. The pipes can be glued or soldered into circular groves prepared in outer surface of yoke. We consider that the yoke diameter will be slightly enlarged; the groves for pipes should not restrict a magnetic flux in the stator core.

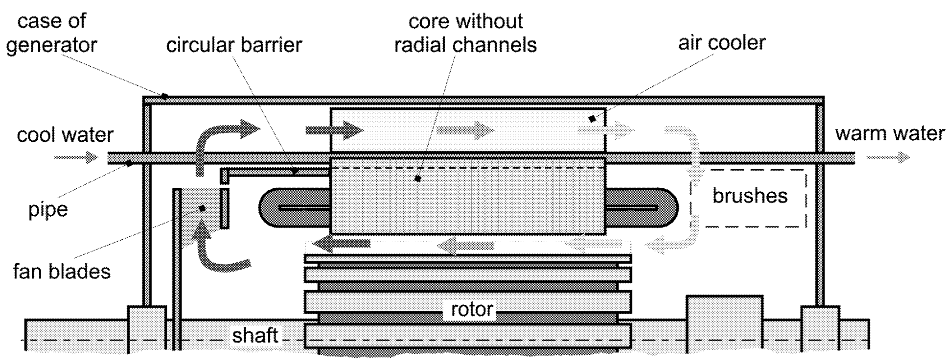

Fig.1: The scheme of proposed water cooling

It is evident that the rotor has to be cooled by air. Therefore, we have to make possible air flow through an air gap. The heat can be removed from air by a special (small) heat exchanger inside the machine. This heat exchanger (air cooler) can consist of metal fins that will be in contact with the cool cooling pipes (see Fig. 2). So, these fins could cool air inside and transfer this rotor-losses heat into water.

3. Thermal resistance of yoke with circular groves for pipes

One of the most important parameters of the proposed water cooling is a thermal resistance of stator yoke. This means the thermal resistance in radial direction between an inner radius of yoke (r_1, see Fig. 2) and circular groves for cooling pipes. This thermal resistance (called as R_j) has significant influence on a thermal difference across stator yoke (and on stabilized temperatures of stator winding). With regard to this, an ability to precise evaluate R_{j} is principal for a design of water cooling parameters.

We derived following formula (based on Fourier's law) for evaluation of the yoke thermal resistance:

$$R_{\mathrm{j}} = \frac{1}{2\,\pi\,L_{\mathrm{z}}\,\lambda\,\chi}\ , \tag{1}$$

where L_{z} is an axial length of yoke, λ is a thermal conductivity of yoke in radial and tangential direction and χ is a dimensionless coefficient related to yoke cross-section geometry which is the only one unknown variable in this relation.

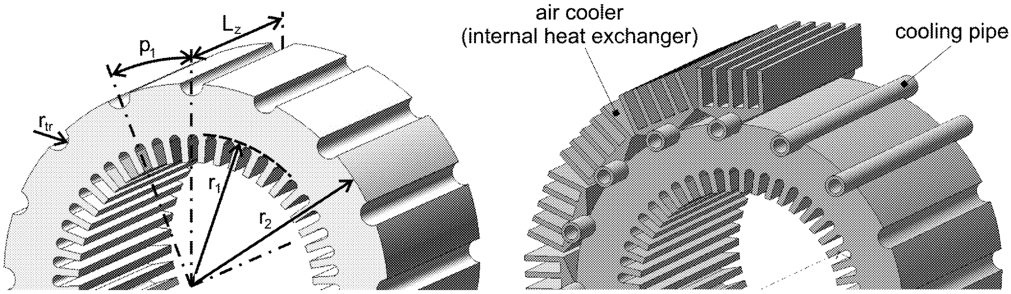

Fig.2: Main parameters of modified yoke

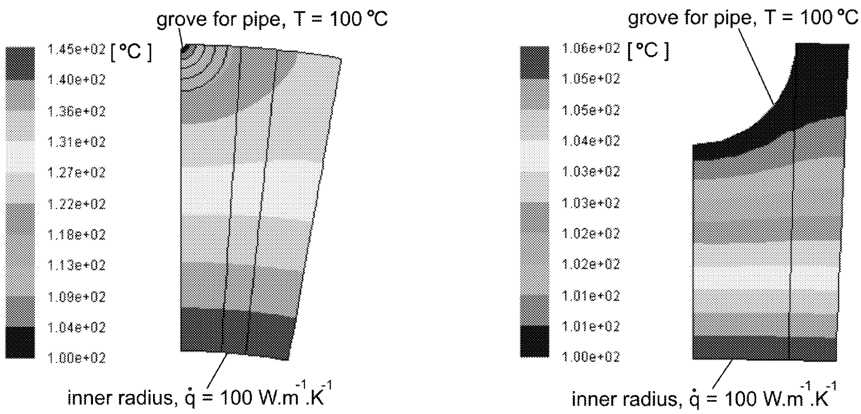

Fig.3: Examples of two FEA models which were used for evaluation of the coefficient χ

We used several finite element analyses (FEA) for evaluation of χ. The used software was Ansys 12. We created a total of 124 FEA models with different combinations of parameters called as p_1, p_2 and p_3. The parameter p_1 means the pitch angle (degrees) between circular groves for cooling pipes (determines the number of circular groves for pipes). The parameter p_2 is given as a ratio of a circular groves radius r_{tr} and an outer radius of stator yoke r_2. The third parameter (p_3) is given as a ratio of an inner radius of yoke r_1 and the outer radius of yoke r_2 (see Fig. 2). The created set of FEA models covers different combinations of parameters p_1, p_2 and p_3 in the following ranges:

- p_1 : 3, 4.5, 7.5, 12, 20, 30 [degrees] (120, 80, 48, 30, 18 and 12 circular groves)
- p_2: 0.005, 0.009, 0.016, 0.026, 0.037, 0.05 [–]
- p_3 : 0.67, 0.79, 0.87, 0.92 [–]

These ranges cover most of the possible realizations of the proposed water cooling. The coefficient χ can be calculated as follows:

$$\chi = \frac{1}{2\,\pi\,L_\mathrm{z}\,\lambda}\,\frac{1}{R_\mathrm{j}} = \frac{1}{2\,\pi\,L_\mathrm{z}\,\lambda}\,\frac{\dot{Q}}{\Delta T} = \frac{1}{2\,\pi\,L_\mathrm{z}\,\lambda}\,\frac{2\,\pi\,r_1\,L_\mathrm{z}\,\dot{q}}{\Delta T} = \frac{r_1\,\dot{q}}{\lambda\,\Delta T}\,, \tag{2}$$

where $\dot{Q}$ is a heat-flow entering at boundary of inner radius of FEA model, $\dot{q}$ is a heat flux at the same boundary (see Fig. 3), λ is a thermal conductivity of the yoke set in FEA and ΔT is a temperature difference between the inner radius of yoke and the surface of grove for the cooling pipe (result of the FEA).

In this way we received appropriate value of χ for each combination of p_1, p_2 and p_3. Then we created a relation that interpolates values of χ, depending on the parameters p_1, p_2 and p_3:

$$\begin{aligned}\chi = 5.636 &+ 3400\,p_1^{-0.785}\,p_2^{0.679}\,p_3^{17.2} - 29083\,p_1^{-1.05}\,p_2^{0.986}\,p_3^{11.2} - \\ &- 9\times10^6\,p_1^{-0.25}\,p_2^{2.92}\,p_3^{42.9} - 2271\,p_1^{-0.35}\,p_2^{0.714}\,p_3^{13.7} + \\ &+ 14206\,p_1^{-0.722}\,p_2^{0.853}\,p_3^{11} + 1.83\times10^7\,p_1^{-0.51}\,p_2^{2.95}\,p_3^{39.6} + \\ &+ 1.34\,p_1^{-0.21}\,p_2^{-0.24}\,p_3^{2.2} - 1.65\,p_1^{0.22}\,p_2^{-0.1}\,p_3^{0.51} - 1.6\,p_1^{-0.46}\,p_2^{-0.008}\,p_3^{-1.76}\,.\end{aligned} \tag{3}$$

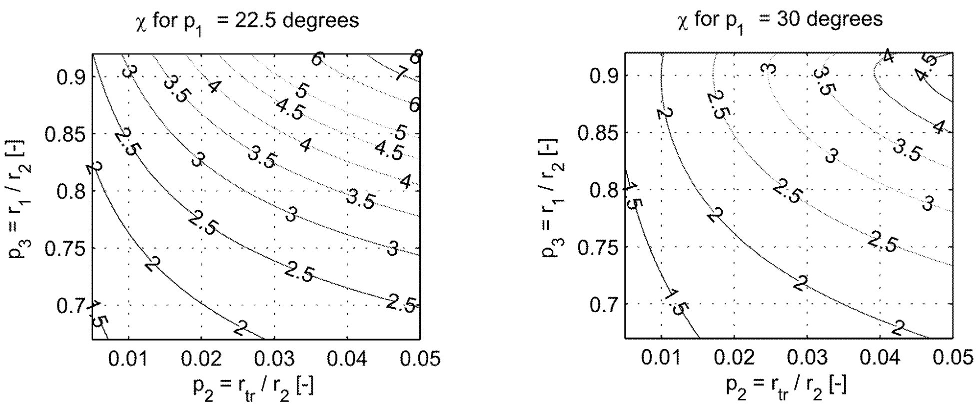

Fig.4: Two examples of coefficient χ behaviours

This relation can help to calculate the thermal resistance R_j for any sizes of stator yoke. So, any further FEA are not necessary. Two examples of χ behaviours (according to the created interpolation (3)) are presented in Fig. 4.

4. Application of the proposed water cooling on a small asynchronous motor

A small induction motor (7.5 kW) was selected for practical verification of the proposed coo-ling concept. We decided on this machine in particular because of its lower cost and facility of modifications, despite the fact that this motor is smaller than the synchronous generators, for which the water cooling is primarily intended.

The applying of the water cooling to this small asynchronous motor offers these benefits:

- The ability of water cooling can be experimentally verified.
- We can detect any adverse effects associated with this method of cooling.

– The measured data can be used for settings of a computational fluid dynamics (CFD) model, through which we can identify some unknown material properties and to quantify the heat flows inside the machine.

A simple thermal network covering the stator was used for calculating of the main parameters of the water cooling. This thermal network takes into account lot of parameters, such as expected losses, a mean target temperature of the stator winding, a mean temperature of cooling water, assumed thermal conductivities of motor parts, assumed heat-transfer coefficients inside the pipes, etc. Through this thermal network, we calculated the maximum allowable thermal resistance of the yoke, R_{j}. Then we calculated the necessary value of coefficient χ (derived from equation (1)). Finally, the parameters p_1, p_2 and p_3 were determined by graphs in Fig. 4.

We had to a few times repeat this procedure because there is an influence of the resulted parameter p_2 on the heat-transfer coefficient inside pipes that is assumed in the thermal network. After a few iterations, we obtained a resulted solution of water cooling parameters. It consists of sixteen grooves for cooling pipes with outer radius 3 mm and inner radius 2 mm (see Fig. 5 left). We had to produce a new housing for the modified stator, see Fig. 5 right. The modified motor fully corresponds to the schema in Fig. 1.

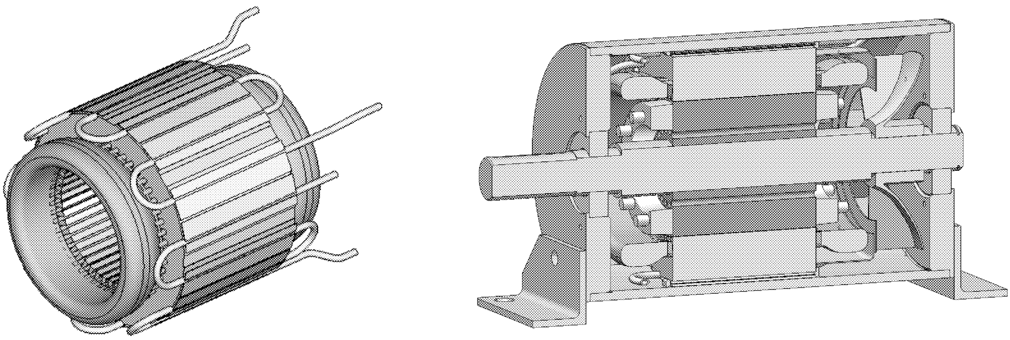

Fig.5: The upgraded stator packet (left) and complete motor with new housing (right)

5. Measurement on upgraded stator

The main objective of this experiment was to specify certain parameters of the modified stator (for purposes of design only the estimated), mainly the thermal conductivities of motor parts. The secondary purpose was to compare the pre-calculated and measured thermal resistance of the yoke.

We used the modified stator packet without motor housing for this experiment. An experiment scheme is presented in Fig. 6. The stator was thermally isolated during the measurement so that the heat generated in the winding (using direct current) could be removed only by cooling water. To measure temperatures, we glued a total of 6 thermocouples on the stator, see Fig. 7. Two other thermocouples (TC1 and TC2) were placed on the input and output of water. The heat input was measured indirectly, through voltage and current. The value of stabilized heat input was 522.5 W. Cooling water flow was measured using a graduated container and stopwatch (0.847 l min^{-1}). All cooling pipes were connected in series during the measurements.

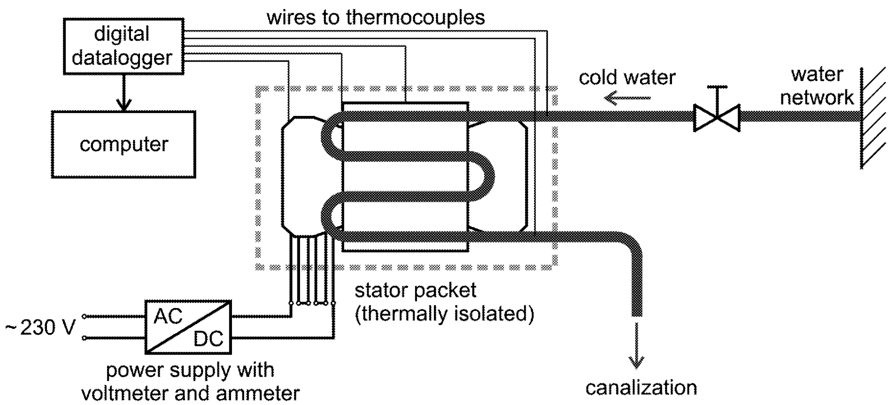

Fig.6: The scheme of experiment

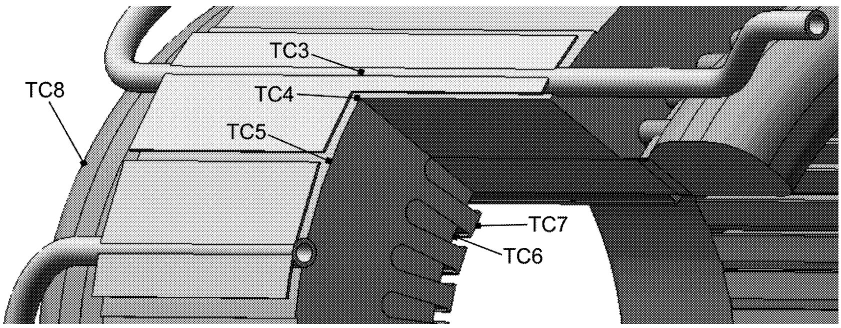

Fig.7: The placement of thermocouples on stator packet

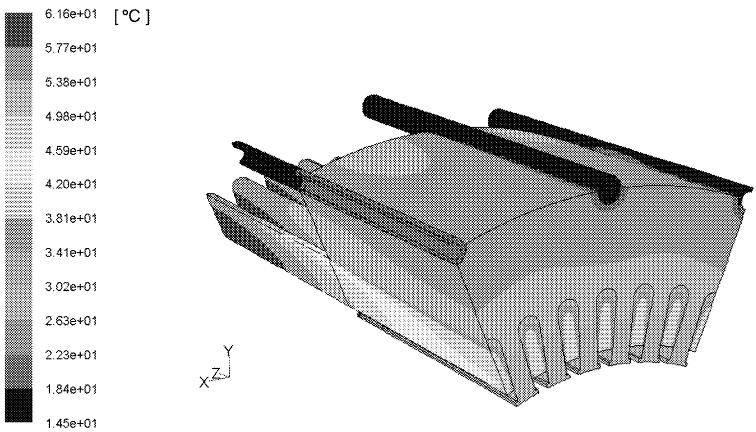

Fig.8: The FEA model of the modified stator packet – contours of temperature

Then (after measurement) we prepared a FEA model of the modified stator. We set appropriate boundary conditions corresponding to real conditions during measurement. Our goal was to minimize differences between measured stabilized temperatures and resulted temperatures of FEA model. For this reason, we tuned the values of thermal conductivities acting in the model. Finally, we achieved differences smaller than 1.5 °C. The contours of resulted temperature are presented in Fig. 8.

Now, we can compare the thermal resistance of yoke R_{j} calculated during the water cooling design and the thermal resistance of yoke calculated from FEA results (called as R_{jFEA}). For this purpose, we need know a mean value of temperature difference between the inner radius of the yoke and grooves for the cooling tubes. This mean value of temperature difference (obtained as yoke-length weighted average by the FEA) is $\Delta T = 7.34\,°\mathrm{C}$ (minimal value is 6.60 °C, maximal 9.56 °C). Then, the R_{jFEA} can be calculated as following:

$$R_{\mathrm{jFEA}} = \frac{\Delta T}{P_{\mathrm{h}}} = \frac{7.34}{518} = 0.142\ [°\mathrm{C\,W^{-1}}]\ , \qquad (4)$$

where P_{h} is the heat input (heat generated at winding). The value of the yoke thermal resistance, calculated during the water cooling design, was $R_{\mathrm{j}} = 0.144\,[°\mathrm{C}\,W^{-1}]$. We can see that the values of R_{j} and R_{jFEA} are almost same. It confirmed the accuracy of the method used in the design of water cooling parameters.

This FEA model also showed a non-uniformity of temperature differences distribution across the yoke length. This non-uniformity related to heat flows from winding overhangs should be taken into account during the cooling design (especially for bigger machines). A thermal reserve considered during the cooling design can help to avoid an overheating caused by the non-uniformity of temperature.

6. Measurement and CFD model of complete motor with the proposed water cooling

Unlike the previous experiment, this measuring was aimed at finding out behaviour of complete motor. For this purpose, the motor was re-equipped with thermocouples. The thermocouple TC2 was glued on outer surface of motor housing, TC3 was placed behind output of air gap between stator packet and housing (to measure temperature of air) and TC4 was placed on the second overhang of winding. Positions of thermocouples TC1, TC5, TC6, TC7 and TC8 were the same as previous measurement. An ambient temperature was measured by independent thermometer. A resistance thermometer (Pt100) was used for measurement of a rotor temperature (see Fig. 9 left). This thermometer was connected to a small recording device which was also located on the rotor. The motor was attached to a test bench and connected to a dynamometer, see Fig. 9 right. Unlike the previous experiment, the water circuit was divided into two parallel branches (eight straight cooling pipes in each branch). This configuration allowed to achieve higher overall water-flow ($3.53\,\mathrm{l\,min^{-1}}$) and lower water temperature rise between inlet and outlet (calculated 6 °C).

The motor was loaded by a constant shaft power during the measurement (6335 W). Within hours, the measured temperatures rise stopped, we also recorded measured values of electrical and mechanical quantities. These values were used for calculating of losses in individual parts of the motor. There was not any significant increasing of losses which could be caused by the copper cooling pipes. It means that there is not any negative effect of pipes on the magnetic circuit of the machine.

Then, a CFD model of this motor was created. Because we were not able to measure heat flows inside machine, the main purpose of this CFD model was to estimate these heat flows. The CFD model, solved by Fluent 12, took into account geometry, losses and boundary conditions equivalent to the real motor. The used thermal conductions were the same as the previous FEA model of the stator. We were able to achieve temperature differences

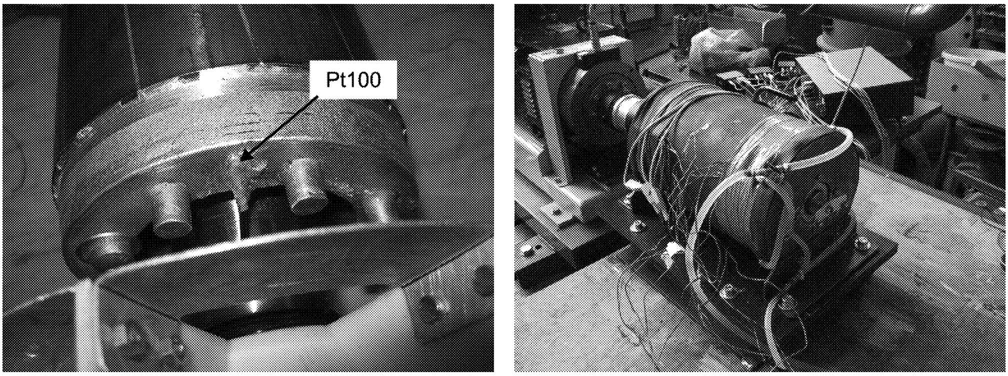

Fig.9: The resistance thermometer Pt100 installed on rotor (left) and the complete motor on test bench before the measurement (right)

(between CFD results and measured temperatures) smaller than 6 °C. It is not as good agreement as the previous FEA model; the CFD model is much more complex and contains fluid zones, therefore the bigger differences are not surprising.

Taking into account results of the CFD model and measured values, we can express an energy balance for the generated heat and heat removed from machine:

$$\Sigma\Delta P = \dot{Q}_{\text{glue}} + \dot{Q}_{\text{fins}} + \dot{Q}_{\text{surf}} = 1274 + 175 + 75 = 1524 \text{ [W]} , \tag{5}$$

where $\Sigma\Delta P$ are total loses (calculated from measured electrical values), $\dot{Q}_{\text{glue}}$is the heat-flow entering pipes through glued joints, $\dot{Q}_{\text{fins}}$ is the heat-flow entering pipes through soldered fins (transferred from air inside machine) and $\dot{Q}_{\text{surf}}$ is the heat-flow heat escaping into the ambient through the outer surface of the machine (free convection and radiation). $\dot{Q}_{\text{fins}}$ and $\dot{Q}_{\text{glue}}$ are results computed by CFD, their sum corresponds to the heat that is removed by water.

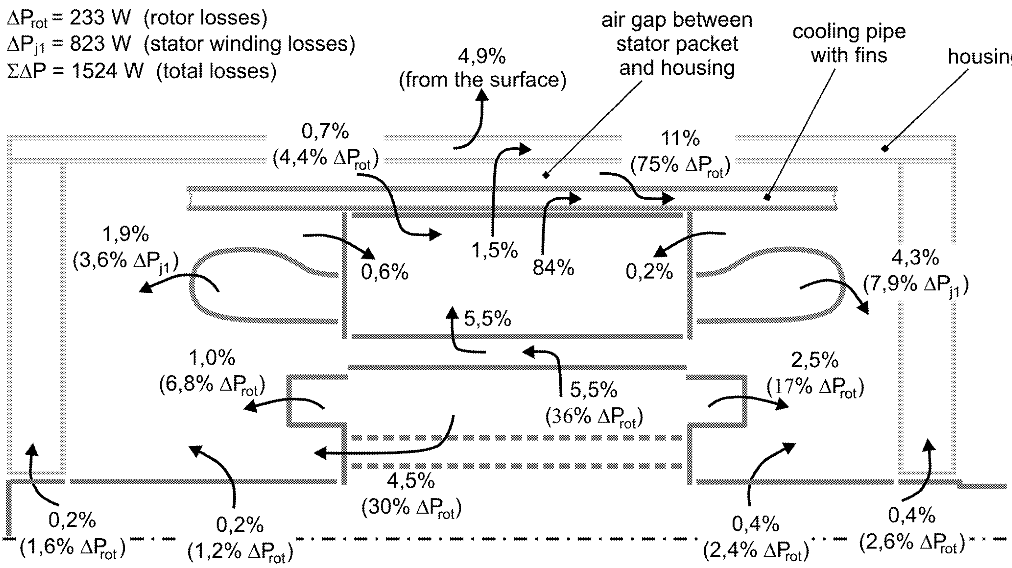

Fig.10: The values of heat flows as percentages of total motor losses $\Sigma\Delta P$

$\dot{Q}_{\rm surf}$ was computed analytically (using measured temperature of motor surface) and set up at the outer boundary of the CFD model.

Another computed values of heat flows, relative to the losses of the machine, are shown in Fig. 10. It is evident that the most of total losses (84 %) is removed through the glued joints between cooling pipes and yoke (heat transfer coefficient $7692\,\mathrm{W\,m^{-1}\,K^{-1}}$). We assume that in the case of bigger machines, this percentage is slightly lower, because the thermal resistance of the yoke will be larger. Therefore, a greater care should be given to internal heat exchanger design in order to improve heat dissipation from air inside.

7. Comparison with otherwise cooled motor versions

For comparison, we carried out similar measurements on other two versions of the motor. The first one was an original (factory-produced) motor cooled by air (outside-placed fan and cooling fins on motor housing). The second measured version emulated the same air-cooling method using for medium-size synchronous generators.

The measuring conditions were very similar – we loaded these two motors by the same shaft power as the previous water-cooled version. A comparison of the most important measured temperatures is presented in Fig. 11. We can see that the water-cooled version is superior to other two air-cooled versions. It is very encouraging that the water-cooled version also showed significantly lower temperature of the rotor. This means that the cooling fins soldered to the pipes perform their function well and sufficiently cool air inside the machine. The proper functioning of the internal heat exchanger will be very important especially in the case of synchronous generators which have rotor with overheating-sensitive winding.

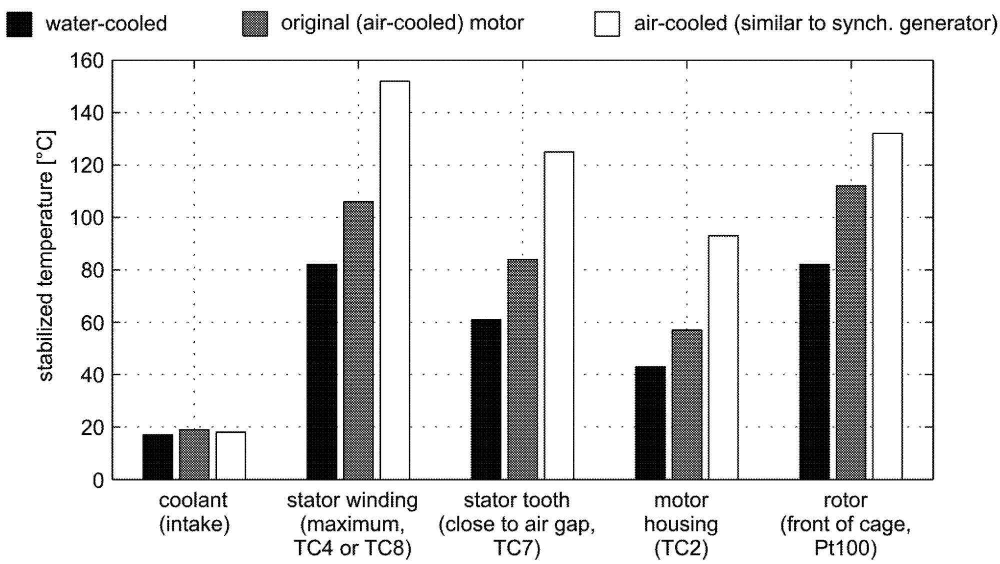

Fig.11: Three versions of the asynchronous motor – stabilized temperatures comparison

8. Conclusion

The presented direct water cooling represents a perspective system of heat removal from electric machines. The stator-mounted water pipes can solve the main problem of air-cooled generators – the big dimensions related to the big external heat exchanger. This external heat exchanger is not necessary to use for presented water cooling; the smaller internal heat exchanger is sufficient to cool air inside the machine because the most of heat is removed directly trough cooling pipes.

The finite element analysis of the modified stator confirmed the correctness of presented design of parameters affecting the thermal resistance of the modified yoke. The derived relations can be used to calculate the thermal resistance of yoke for any machine with this type of water cooling.

The experiments carried out on small water-cooled asynchronous motor showed very good efficiency of the proposed cooling method. The water-cooled motor can achieve a much lower stabilized temperatures than the other two air-cooled variants. With regard to this, the motor can reliably work with substantial overloading.

The future work should be focused on an accurate determination of the heat, leaving the stator directly through the yoke and heat, leaving the stator indirectly through air inside machine. Then, the design of water cooling parameters can be more precise, as well as a design of internal heat exchanger.

Acknowledgments

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