SPRAY COOLING OF PLAIN SURFACES WITH A HIGHLY VISCOUS MODEL FLUID

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1 INTRODUCTION

With the trend towards smaller and high power-density electrical machines, the thermal design of the machine is becoming increasingly important. Accordingly, efficient cooling systems are necessary to keep the operating temperatures of the components within the permitted range and to reduce aging processes, as for example in the windings. In this contribution a measurement concept is presented, which enables a local resolution of the single-phase heat transfer of spray cooled end windings. In literature, only a limited amount of measurement data are available on the single-phase heat transfer of spray cooled plain surfaces with highly viscous coolants, e.g. oils. Therefore, this work first focusses on identifying the essential dependencies, such as material properties or operating parameters of spray cooled plain surfaces. First measurements were conducted using a model fluid concept, with the aim of covering a wide range of commercial gearbox oils.

2 MODEL FLUID

In order to select a suitable model fluid, different binary solutions were compared using two dimensionless numbers, the Ohnesorge number $(Oh = \eta_\mathrm{f}/\sqrt{d_0 \cdot \rho_\mathrm{f} \cdot \sigma_\mathrm{f}})$ and the Prandtl number $(Pr = \eta_\mathrm{f} \cdot c_\mathrm{p,f}/\lambda_\mathrm{f})$, with the nozzle outlet diameter d_0 being the characteristic length. The selection was based on these two numbers, as they are both critical metrics for the atomization and the thermal transport processes during spray cooling. Simultaneously, they are independent from the operating conditions, hence they primarily represent the influence of the fluid properties. All required material properties have been experimentally determined in a temperature range of 30 °C - 90 °C. It was found that aqueous glycerol solutions are most suitable to cover the range of Oh and Pr numbers of commercial gearbox oils. Table 1 shows the Oh and Pr numbers of two aqueous glycerol solutions (78 Ma% G and 95 Ma% G) and one commercial gearbox oil of type ATF VI.

Table 1: Oh and Pr numbers of two aqueous glycerol solutions and a gearbox oil of type ATF VI as a function of temperature. The expended uncertainty according to GUM B ($k=2$) is shown in brackets.

Coolant /-	Temperature range / °C	Oh / -	Pr / -
Aqueous glycerol (78 Ma% G)	30 - 90	0.092 - 0.015 (0.004 - 0.0007)	196 - 31 (8.5 - 1.3)
Aqueous glycerol (95 Ma% G)	30 - 90	0.888 - 0.047 (0.038 - 0.002)	1948 - 102 (84.2 – 4.4)
Gearbox oil, type ATF VI	60 – 90	0.081 - 0.047 (0.0027 - 0.0016)	185 - 110 (6.7 - 4)

Both solutions cover the entire range of Oh and Pr numbers of the gearbox oil in its operating temperature range (60 °C - 90 °C). In addition, the model fluid allows an investigation of spray cooling heat transfer outside the operating range of the ATF VI gearbox oil (see Table 1). In the scope of this

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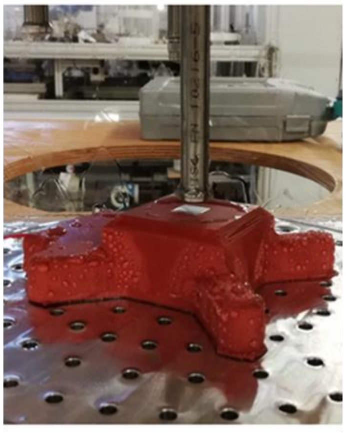
work, several compositions of the model fluid between 88 Ma% G – 92.5 Ma% G have been used. Following common terminology, we use the term „single-phase“ to emphasize the fact that the fluid is well below boiling temperature under all conditions and thus no nucleate boiling effects occur. Nevertheless, the spraying process, from atomization to the impact of droplets on the surface, is a complex multiphase flow phenomenon.

3 EXPERIMENTAL SETUP

A single-phase flow loop was set up, consisting of two main components, a thermostat circuit and a spray chamber. The thermostat circuit consists of a thermostat and a bypass control that provides tempered model fluid. The flow rates are measured by a Coriolis mass flow meter. From the thermostat circuit, the model fluid is fed into the spray chamber and atomized via a full cone nozzle of the manufacturer Schlick (model 553, size 0, spray angle 45°). The fluid temperature and pressure drop at the nozzle outlet are determined with a platinum resistance sensor and a relative pressure sensor.

Figure 1 shows a depiction of the measurement concept. All heat transfer measurements are conducted inside a spray chamber with various test pieces (see Figure 1). Each test piece consists of a temperature-resistant silicone structure with a measuring element (ME) embedded at its centre (see Figure 1). The T-shaped ME are made of an aluminium (AW-2007) or a copper alloy (Cu-ETP). The local heat transfer coefficient α_{local} is determined at the smooth surface of the ME, where droplet impingement occurs. The bottom of the ME is contacted with an electrical resistance heater. Gap fillers between the measuring element and the resistor were used to reduce contact resistances and to ensure homogenous heat dissipation over the cross-sectional area of the ME. Assuming one-dimensional heat conduction, the mean surface temperature T_{surface} is extrapolated from the measurement data of four thermocouples (type K) distributed over two measuring planes (MP 1 and MP 2). The various thermal transport paths within the measuring elements are accounted for by a weighted combination of parallel and series connections of thermal resistances. The local heat transfer coefficient can be calculated through a combination of heat conduction in the ME and the kinetics of heat transfer on the spray cooled ME surface.

The dimensions of the heat-transferring surface of the measuring elements (12.7 mm x 12.7 mm) as well as the surrounding surface of the silicone structure (43.5 mm x 43.5 mm) were based on the work of K. A. Estes and I. Mudawar [1]. The silicone structures serve two main purposes: they prevent the spray from hitting the sides of the measuring elements and they provide a controlled fluid drainage, which is similar to larger surfaces. In the scope of this work, all measurements were performed with smooth surfaces of the measuring elements and the silicone structures (see Figure 1).



test piece in spray chamber

Figure 1: Depiction of the measurement concept with a test piece inside the spray chamber.

4 MODELLING SINGLE-PHASE HEAT TRANSFER

When modelling the single-phase heat transfer of spray cooling, two processes must be taken into account. First, a liquid sheet emerges from the nozzle orifice, which disintegrates and results in a spray of various droplet sizes, droplet velocities and droplet trajectories. Secondly, the droplets impact on the measuring element surface at locally varying volumetric spray fluxes. To handle both complex processes, averaged hydrodynamic quantities are used. The spray is characterized using the Sauter mean diameter d_{32} (SMD), assuming a monodisperse droplet distribution with a volume-to-surface area ratio representative of the actual spray (see Eq. (1)).

$$d_{32} = 6\frac{V_{\mathrm{D}}}{A_{\mathrm{D}}} = \frac{\sum_{i=1}^{\mathrm{n}} d_i^3}{\sum_{i=1}^{\mathrm{n}} d_i^2} \tag{1}$$

However, the experimental determination of the SMD at varying operating parameters and material properties is very expensive and time consuming. Therefore, a correlation for the SMD of full cone nozzles by K. A. Estes and I. Mudawar [2] is used (see Eq. (2)). The presented validity range of the correlation was determined from their measurement data.

$$d_{32} = 3{,}67 \cdot d_0 \cdot \left(\sqrt{We_{d_0}} \cdot Re_{d_0}\right)^{-0{,}259};\ 9.5 \cdot 10^3 < Re_{d_0} < 9.1 \cdot 10^4 \text{ and } 1.8 < We_{d_0} < 75 \tag{2}$$

The correlation is based on an approach of A. H. Lefebvre [3] to describe the first stage of the atomization process due to hydrodynamic and aerodynamic forces. He suggests to combine the Reynolds $\left(Re_{d_0} = \rho_{\mathrm{f}}(2\Delta p/\rho_{\mathrm{f}})^{1/2} d_0/\mu_{\mathrm{f}}\right)$ and Weber numbers $\left(We_{d_0} = \rho_{\mathrm{a}}(2\Delta p/\rho_{\mathrm{f}}) d_0/\sigma_{\mathrm{f}}\right)$ according to Eq. (3). Here, ρ_{a} is the density of the ambient fluid (air).

$$\frac{d_{32}}{d_0} \propto \left(\sqrt{We_{d_0}} \cdot Re_{d_0}\right)^{-x} \tag{3}$$

The above SMD correlation is based on FC-72 and water measurements with varying orifice diameters (0.76 mm -1.7 mm) covering the entire Weber number range of the model fluid (4 -30). However, the Reynolds numbers (910 - 3300) exceed the validity range of the correlation. Therefore, its application is not expected to provide precise absolute values of the SMD, but a correct description of the functional relationship between the operating conditions, medium and the droplet diameter. In future work, the SMD will be studied in more detail to accurately verify the applicability of Eq.(2).

The second hydrodynamic parameter required for modelling the single-phase heat transfer is the average volumetric flux $\dot{V}''_{\mathrm{ME}}$ on the surface of the ME. In the work of K. A. Estes and I. Mudawar [1], a model is presented (see Eq. (4)), which describes the radial distribution of the volumetric flux $\dot{V}''$ in full cone sprays as a function of the radial location r, the spray angle θ as well as the volumetric flux averaged over the entire cross-sectional area of the spray cone $\bar{\dot{V}}''$ at a certain distance z_{Nozzle}.

$$\dot{V}'' = \frac{1}{2}\bar{\dot{V}}''\left[\frac{\tan(\theta/2)}{1-\cos(\theta/2)}\right]\left[1+\left(\frac{r}{z_{\mathrm{Nozzle}}}\right)^2\right]^{-3/2} \tag{4}$$

By integration of Eq. (4), the volumetric flow $\dot{V}(r)$ impinging on a circular surface section of radius r at a certain nozzle-to-surface distance z_{Nozzle} is calculated (see Eq. (5)).

$$\dot{V}(r) = \int_0^r \dot{V}''\, 2\pi r dr \tag{5}$$

In the scope of this work only nozzle-to-surface distances $\left(z_{\text{Nozzle}} \geq b/(2\tan(\theta/2))\right)$, where almost the entire ME surface is covered by the spray, are investigated. Thereby b is the edge length of the ME. To determine the absolute volume flow $\dot{V}_{\text{ME}}$ impacting on the ME surface, two cases depicted in Figure 2 must be differentiated. For high nozzle-to-surface distances $\left(z_{\text{Nozzle}} > b/(2\tan(\theta/2))\right)$, only a fraction of the total volume flow impacts the ME surface (see Figure 2 (A)). In this case, $\dot{V}_{\text{ME}}$ is determined by using $r = 0$ and $r = b/2$ as integral limits of Eq. (5). For small nozzle-to-surface distances $\left(z_{\text{Nozzle}} = b/(2\tan(\theta/2))\right)$, the impact area of the spray is smaller than the ME surface (see Figure 2 (B)). In this case, $\dot{V}_{\text{ME}}$ equals the total volume flow $\dot{V}$ exiting the nozzle orifice.

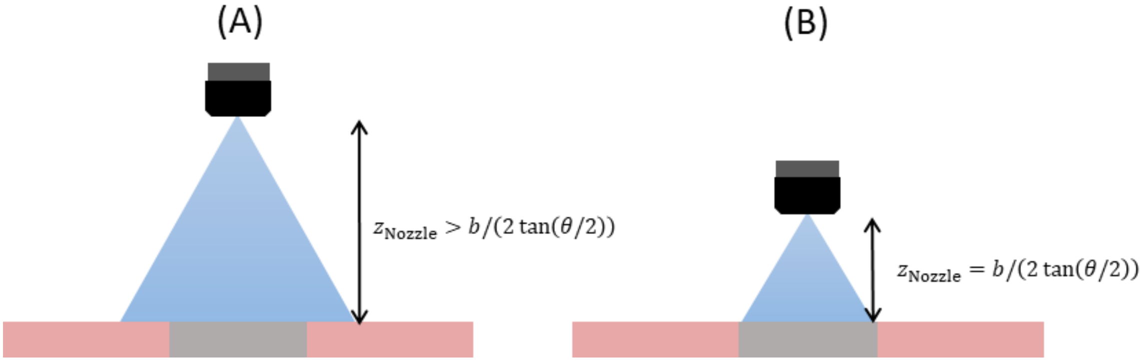


Figure 2: Depiction of the relation between the impact area of the spray and the ME surface area at varying nozzle-to-surface distances.

The average volumetric flux $\dot{V}''_{\text{ME}}$ is calculated by dividing $\dot{V}_{\text{ME}}$ by the ME surface area A_{ME}. The surface area of the ME was selected as the reference for both cases (A) and (B), since it corresponds to the heat transferring surface area, which is, in most cases, completely covered by the spray.

When both averaged hydrodynamic quantities (d_{32} and $\dot{V}''_{\text{ME}}$) are known, the Nusselt number $Nu_{d_{32}}$ is calculated as a function of the Prandtl number Pr and the Reynolds number at droplet impact $Re_{\text{d}_{32}} = \rho_{\text{f}} \dot{V}''_{\text{ME}} d_{32} / \eta_{\text{f}}$ (see Eq. (6)). Thereby a_1, a_2, a_3 are constants fitted to the measurement data.

$$Nu_{d_{32}} = \frac{\alpha_{\text{ME}} \cdot d_{32}}{\lambda_{\text{f}}} = a_0 \cdot {Re_{\text{d}_{32}}}^{a_1} \cdot Pr^{a_2} \tag{6}$$

5 RESULTS AND DISCUSSION

All data points presented in this contribution were determined at nozzle-to-surface distances ranging from 15 mm to 100 mm. These values were chosen for several reasons: As stated above, the spray covers almost the entire ME surface. Therefore, the ME surface can be considered as the heat transferring surface. Additionally, hydrodynamic effects, such as the hydraulic jump, are avoided, as these would affect the measurement results. Finally, the distances are relevant for the practical use in electric machines. In a first step the measurement data of this work was compared to the few correlations available in the literature by J. R. Rybicki, I. Mudawar and W. S. Valentine [4,5]. However these correlations are limited to a range of low Pr numbers and therefore inadequately describe the data of this work with deviations exceeding one order of magnitude.

Figure 3 shows the single-phase data of various model fluid solutions in the range of the Pr and Oh numbers of an ATF VI gearbox oil (see section 2).

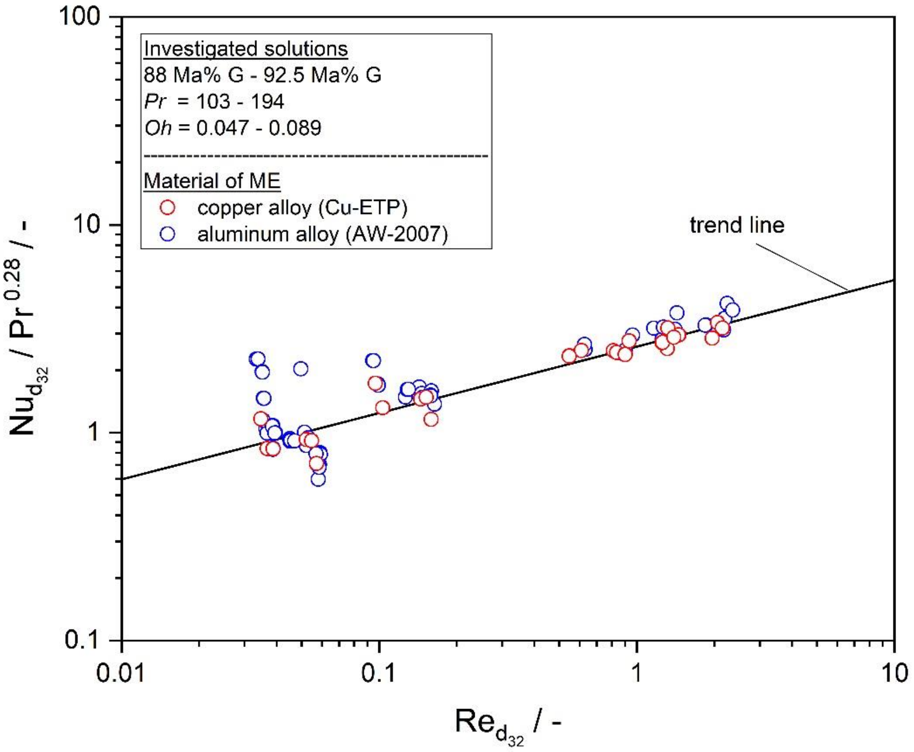


Figure 3: Single-phase heat transfer data of highly viscous model fluid sprays in the Pr and Oh range of a gearbox oil of type ATF VI.

The data are plotted as a quotient of the Nusselt number and the Prandtl number. The dependence of the Prandtl number to the power of 0.28 was determined from the measurement data by the method of least squares. The purpose of this plot is to eliminate the dependence of the Nusselt number on Prandtl number and thus to enable a better investigation on the influence of the Reynolds number. The depicted data show, that by increasing the volumetric flux, respectively the volume flow impacting on the ME surface, the heat transfer improves. By comparing the trend line and the measured data, it is apparent that the measured data exhibit a clear dependence on the Reynolds number, suggesting an applicability of Eq. (6). Larger deviations at low Reynolds numbers respectively high nozzle distances are caused by the spray angle, which was kept constant during the calculations. However, the experiments showed some variation of the spray angle depending on the present operating conditions. In future work, this effect will be analysed in more detail. With identical operating parameters and material properties of the model fluid, the measurement data for both ME agree well and show no systematic deviations. Consequently, the influence of the ME material on the wetting behaviour and heat transfer at the surface of the test pieces appears to be negligible. In summary, the heat transfer of spray cooling with highly viscous fluids can be expressed as a function of the Reynolds and the Prandtl numbers. However, the development of a correlation following the approach of equation (6) requires a larger data base. In future measurements, not only additional operating parameters but also different full cone nozzle types will be investigated to develop a precise correlation of the single phase heat transfer.

6 CONCLUSION

A concept for experimental investigation of spray cooling of plain surfaces with a highly viscous model fluid in the range of Prandtl and Ohnesorge numbers typical for a commercial gearbox oil of type ATF VI was presented along with some first experimental results.

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