Assessment of the flow induced corrosion behaviour in generic pipe conduits used in modern engine cooling systems

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Abstract

With respect to an increased downsizing of internal combustion engines and therefore the use of intelligent thermo-management, the requirements for cooling systems and the coolant itself are growing progressively. Both efforts result in an increased heat input and thermal stress of the coolant as well. Along with this, highly stressed zones can lead to an excessive material degradation caused by interacting boiling effects, cavitation, erosion, and corrosion. These complex interactions and degradation issues are rarely investigated yet.

The overall objective of this work is to create an assessment method taking superimposed corrosion stresses into account and to predict and avoid excessive material degradation in automotive applications. Channel geometries mimicking typical engine component features were examined in a first step with regard to potentially damage-critical areas. Among the required developments and modifications are the novel, fully automatically operating fluid dynamic corrosion test facility (FDC) as well as a specially designed sample chamber, which can detect the channel induced change of heat input at the sample surface area. In addition, flow characterization of the cooling canals via Laser-Doppler-Anemometry (LDA) is possible, that is implemented on the sample chamber.

The identification of damage-causing interactions is also possible, based on a phenomenological evaluation of degradation and layering processes. First results showed that high flow velocities lead to severe degradation phenomena in cooling channels. Critical stress parameters (e.g. extensive shear stresses across the boundary layer) were identified and evaluated with respect to their erosive degradation potential. This allows differentiating between flow-induced material degradation (erosion) and superimposed corrosive stress as a basis for enhanced simulative concepts. As an outlook for subsequent investigation, the characterization and evaluation of the flow state as a function of the medium composition and surface conditions is possible, hence correlations can be established between the demands on the component and degradation states and thus the safety during operation will be optimized.

Keywords

Cooling systems, flow dynamic corrosion test method, flow velocity, corrosion, erosion, cavitation, monoethylene glycol, MHTA, FVV Guideline R530-2005

1 Introduction

Efforts to reduce greenhouse gas emissions in the transport sector require new innovative drive technologies. In addition to fully electric drive systems (BEV) and fuel cells (FCEV), which are currently under discussion, development is also focusing on optimization concepts for combustion engines (ICE) and hybrid vehicles (PHEV), particularly in the heavy-duty sector. In the recent past, conventional internal combustion engines have therefore been adapted for emission and cost reasons [1] [2]. The aim was to reduce engine cubic capacity (downsizing) while simultaneously optimizing performance and reducing fuel consumption. At the same time, developments also took place in the area of thermal management systems [1] [3]. All thermal management concepts control heat dissipation by cooling media. The geometric structures of such coolant channel systems can be abstracted to elementary geometric units. The influencing variables of heat input, channel geometry, deflections, branches and confluences as well as the material used play the most important role concerning the material stress and also with regard to general efficiency. The material optimization possibilities and test methods used for characterization and suitability of selected coolants on material surfaces are investigated. The inhibited coolant, which has to dissipate large amounts of heat to protect the materials and at the same time prevent cavitation and corrosion attacks, is extremely stressed by the rising engine peak temperatures. In addition, higher flow velocities are required for rapid heat dissipation. The influence of the increased velocities on the degradation of the materials has not yet been researched. At the same time, due to the more compact vehicle design, the available space in the engine compartment is becoming more and more restricted, which leads to increased thermal loads and lower coolant volumes. In order to avoid critical temperatures of the components by means of more intensive cooling, even local boiling of the coolant is permitted or deliberately used in today's engine development, since condensation cooling improves heat dissipation. Modern and conventionally available coolants consist of a mixture of water and usually 30 to 50 % (volume fraction) coolant additives, whereby the additives consist of ethylene glycol for freeze protection and corrosion inhibitors for corrosion protection of the materials. In order to assess the suitability of coolants for an appropriate cooling system, vehicle tests offer good possibilities. However, such tests are cost-intensive as well as time-consuming and are only suitable to a limited extent for the evaluation of coolants within a development phase. For fundamental research and development, practical investigation methods in a laboratory scale for clarifying and evaluating the interaction between coolants and materials with regard to corrosion protection of in future mobility concepts are therefore be needed.

2 Standard Test Methods

To qualify coolants and materials with regard to their corrosion properties use, a variety of test methods are available. In addition to static tests (ASTM D 1384, ASTM D 4340), tests on actively heated samples in the flowing medium have been established due to the good transferability of results to service-oriented systems. These include, for example, the German guideline FVV R530/2005 and the French test standard GFC Fl-23-X-09.

2.1 Test Method according FVV Guideline R530-2005

Due to the large number of physical factors influencing the behavior of coolants and materials in cooling circuits, complex technical requirements within a test facility are necessary in order to be able to reproduce scientific results in a comprehensible manner. Using the so-called modular hot test facility (MHTA), standardized tests according to the FVV guideline R530-2005 are possible, whereby modern coolants can be tested for stability at elevated temperatures, pressures and flows as well as for the long-term behavior of corrosion inhibitors [4] [5]. These factors limit the applicability of coolants. When selecting moderate test run times, layer formation or corrosion processes occur. The material samples can also be tested for ageing or depletion processes of the inhibitors in the coolant [6]. The so-called modular hot test facility (MHTA) consists of several modular test modules [5] [7]. The modularity allows a differentiated investigation of the inhibition concept and the performance of coolants under complex loading conditions. All components used for coolant guidance in peripheral modules are made of inert plastics (PTFE, PFA, PVDF and PEEK). A high-alloy austenitic CrNi steel (material no. 1.4571, AISI 316Ti) is used for the piping systems and fittings, which has excellent material compatibility in conventional coolants. Thus, sample materials can be selected and introduced into the circulation system individually or in any combination in order to realize the desired material combinations, which are also available in modern engines or cooling systems. With additional coolant variation, this results in an instrument for complex investigation of the interaction between materials and coolants. The schematic test system design is shown in ***Figure 1*** and the technical test data can be taken from the following ***Table 1***. ***Figure 2*** shows the installation of the actively heated sample (***Figure 3***) and the flow through the sample ring.

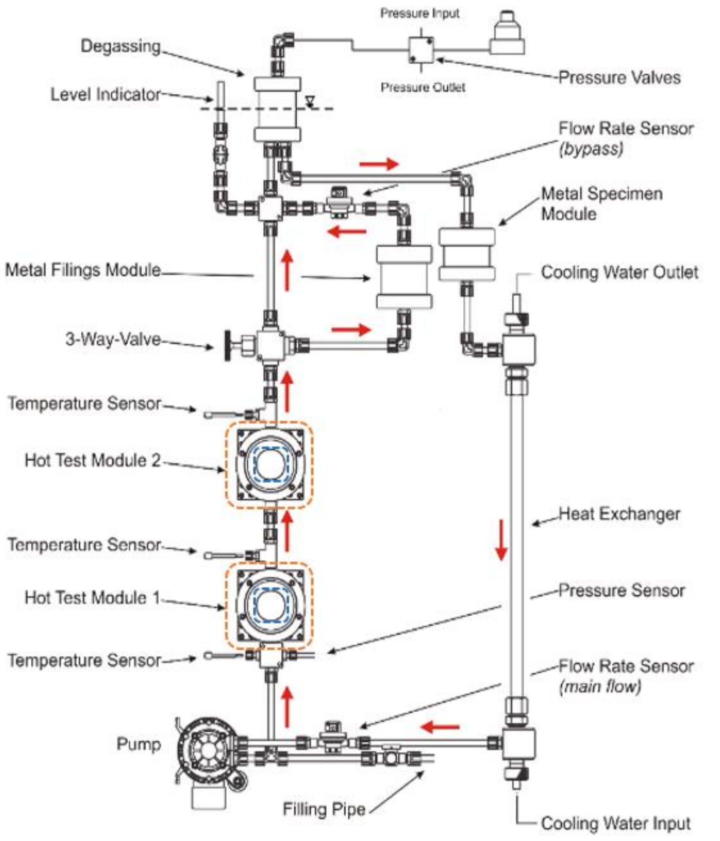


Figure 1*: Schematic experimental Set-up of the modular hot test facility (MHTA)* [1]

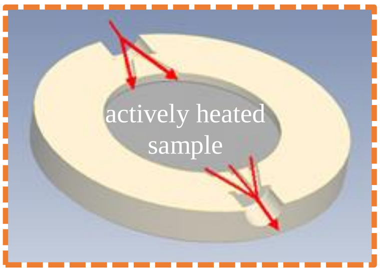


Figure 2: *CAD of sample chamber ring; actively heated sample an flow direction* [2]

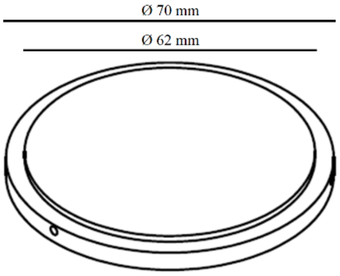


Figure 3: *MHTA Sample according FVV R530-2005*

2.2 Evaluation of the Standard Tests

Established static immersion tests show the influence of thermal stress on a coolant. The heat input is both indirect (ASTM D 1384) and active via a heated material sample (ASTM D 4340). However, both investigations do not take into account the influence of a superimposed flow. Erosion and cavitation in particular are flow-induced stresses. In addition, influences on the boundary layer behavior, e.g. in connection with the re-passivation or formation of reaction layers with the coolant, must also be specified. The influence of changing test cycles with hot and rest phases, which cannot be neglected, leads to phenomena in the formation or regeneration of reaction layers. Due to the temperature change, these layers suffer thermal expansion and crack during the transition into the hot phase, which can lead to corrosion of the material. Liquid flows during the hot phase can, from today's point of view, influence the existing surface layers due to their abrasive effect. Due to the high complexity of a cooling system and the increased technical requirements with regard to the stresses on materials and coolants, the methods described are limited regarding their suitability to qualify modern coolants for use, ***Table 1***. Especially for the evaluation of the flow dynamic corrosion behavior at increased coolant temperatures, higher heat flux densities, constant overpressure, defined flow velocity and changing temperature cycles, more complex investigation methods are necessary. As described in ***Chapter 2.3***, the MHTA test facility of the test guideline FVV R530-2005 is better suited for this purpose, as it has a higher significance with regard to the practical relevance and the long-term behavior of coolants used and their interaction with different materials. The long-term behavior of coolants is tested by defined time-lapses. The system stands still for a certain period of time so that the coolant cools down and the coolant repassivation properties can be investigated over several hours. However, the effect of the different geometries of the coolant flow channel is considered which has the greatest influence on the degradation mechanisms such as erosion and cavitation as well as boiling-induced material degradation. This means that such test methods have to necessarily extended to approach the complex operating conditions in real cooling systems of internal combustion engines. The test method "Flow Dynamic Corrosion Test" (FDC) developed for this purpose makes use of elementary channel guide geometries to investigate the influence of the filigree channel flow. In the following chapter, the test method is explained in more detail.

Table 1: *Comparison of different approved test methods; extension of* [2]

Parameters influencing the corrosion	ASTM D 1384	ASTM D 4340	MHTA	FDC
Sample temperature	Unheated metal sample bundle	Heated aluminum sample, T = 135 °C	− 2 hot samples (self-regulating temperature) − 2 unheated circular samples − Unheated metal samples − Fouling sample	− 1 hot sample (self-regulating temperature) − 1 unheated circular sample
Heat flux	Not defined	Not defined	Constant, up to 90 W/cm^2	Constant, up to 700 W/cm^2
Coolant temperature	88 °C	Not defined	80 – 130 °C	60 – 120 °C
Influence of fluid flow	Not defined	Not defined	Flow rate adjustable	Flow rate adjustable
Pressure	Ambient pressure	1,931 bar	Up to 5 bar	Up to 5 bar, Measurement up to 4 bar
Changing test cycles	Not defined	Not defined	Adjustable	Adjustable
Sample specification	50,8 x 25,4 [mm] Flat	65 mm diameter, 1,3 mm thick Flat	Test sample area: 30,2 cm^2 Flat	Test sample channel area: Complex Pipe Flow: 7,6 cm^2 Pipe Flow: 3,4 cm^2 Channel
Test water	Distilled/ deionized water + Na_2SO_4 + NaCl + $Na(HCO_3)$	Distilled/ deionized water + NaCl	− Deionized water − Deionized water + $CaCl_2$ + $MgCl_2$ + $Ca(HCO_3)_2$ + $CaSO_4$ + $MgSO_4$ + $Mg(HCO_3)_2$	− Deionized water − Deionized water + $CaCl_2$ + $MgCl_2$ + $Ca(HCO_3)_2$ + $CaSO_4$ + $MgSO_4$ + $Mg(HCO_3)_2$
Sample surface	Approx. 170 cm^2	Approx. 33 cm^2	Including ASTM Sample bundle up to 6000 cm^2	Complex Pipe Flow: 114,4 mm^2 Pipe Flow: 101,3 mm^2

3 Implementation of a Complex Test Method

3.1 Flow Dynamic Corrosion Apparatus and Method

Like the MHTA, the Flow Dynamic Corrosion (FDC) system is also designed as a fully automated circulation system, ***Figure 4 a)*** and is used for the differentiated investigation of the effect of coolants on different materials under complex stress conditions. In contrast to the MHTA, the FDC facility has a smaller coolant flow rate and a reduced pipe length. The available inhibitors of the coolant quantity are adapted to the sample surface to be tested. Metal chip modules and metal sample holders for ASTM D 1384 sample packages are omitted in order to focus the assessment to the surface of the pipes. The test rig is currently operated with samples of the materials AlSi6Cu or EN GJL 250 and a mixed installation of both or different materials is deliberately avoided. All coolant-carrying components are made of inert plastics (PTFE, PFA, PVDF and PEEK) and piping of high-alloy steel (AISI 316Ti) in order to exclude superimposed corrosive effects. The material samples to be tested, cf. ***Figure 4 b),*** are fixed in a sample holder and one of the two required samples is heated at the back using a block heater, ***Figure 4.***

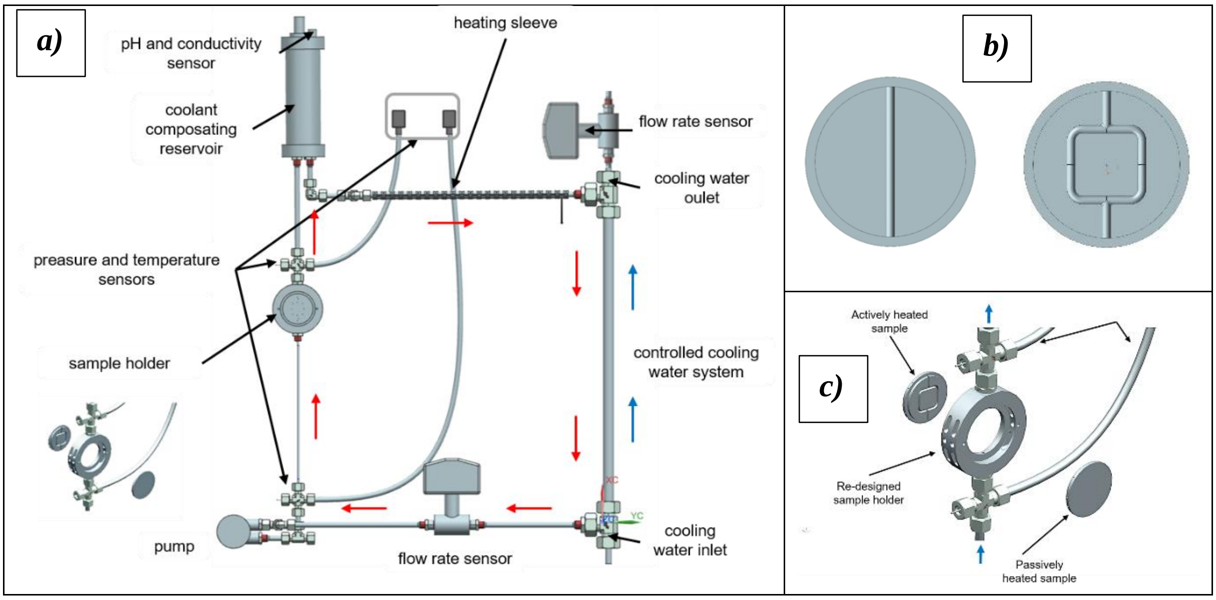


Figure 4: *New Developments;* ***a)*** *Schematic view: Set-up of the flow dynamic corrosion apparatus (FDC);* ***b)*** *Developed samples with* $\emptyset_{\boldsymbol{outside}} = \mathbf{70\,mm}, \emptyset_{\boldsymbol{inside}} = \mathbf{62\,mm\ and}\ \ \emptyset_{\boldsymbol{canal}} = \mathbf{3,5\,mm}$; *Straight Pipe Flow (left), Water Spider (right) ;* ***c)*** *Modified sample holder*

Pressure, temperature and flow sensors control the system and the data is recorded and saved in a database by software. Temperature sensors, which register the heat distribution and are subsequently useful for test evaluation, can be used by means of targeted boreholes, which lie precisely and just below the respective channel surface. The examination principle can be explained as follows: The coolant is set in motion by a chemically resistant pump. The flow length to the sample chamber inlet was mathematically designed to the channel diameter so that a constantly reproducible fully developed turbulent flow occurs upstream of the sample chamber inlet. The coolant passes through the respective sample channel guide and is subjected to heat by the heated lower sample. A total pressure difference is measured by attaching pressure sensors before and after the sample. The aim of the recorded pressure change is to be able to assess in more detail the relationship between the surface layer formed and the corrosion progress as well as the erosive input. This enables the detection of locally prevailing phenomena at relevant points within the cooling channel of the sample. Above all, a better understanding of the inhibition behavior of the coolant at limiting flow velocities can be investigated. In the future, the setup will be able to provide practical assistance when it comes to the design of filigree cooling channel sections. In general, the pressure loss of a hydraulic system depends on the surface roughness of the wall and the flow that occurs. Electrochemical corrosion and the formation of top layers lead to a change in surface and a change in pressure. In general, wall friction and dissipation influence the pressure loss in pipes, fittings and valves. Within the FDC test, for example, in addition to the flow-induced pressure loss caused by wall shear stress and internal friction described above, a superimposed pressure change caused by erosion or cavitation can also be recorded. The formation of cavitation can be explained by the Bernoulli Law. The faster a fluid flows, the lower the static pressure of the fluid. If the static pressure falls below the evaporation pressure of the fluid, vapor bubbles form. If a sudden increase in pressure occurs, for example when the fluid flows from a narrow point (nozzle) into a diffuser, the vapor suddenly condenses in the bubbles and they implode. The resulting pressure and temperature peaks lead to so-called microjet impact, which damages the underlying surfaces and leaves behind a crater landscape [3]. In addition, the pH value and conductivity sensors installed in the expansion tank allow the intensity of electrochemical corrosion to be observed. When ions enter the solution by electrochemical corrosion, the result is a change in conductivity. The continuous pH measurement provides an insight into the decomposition process of the coolant, which is associated with an acidification of the coolant. The mounting of the sensors in the expansion tank is due to the sensitivity of the sensors. The sensors must not be installed in the impingement flow, since the locking device in the tank cover can be loosened by fluid shocks transmitted via the sensor and this can lead to leakage of the system. In order to heat the coolant to the desired test temperature, an additional heat input is installed into the coolant line by a specially developed high-performance cartridge heater. The heat transfer area of the respective test samples is 101 mm^2 (Straight Pipe Flow) and 114 mm^2 (Complex Pipe Flow). The small transfer surfaces lead to rapid overheating of the samples and are therefore supported by the additional heat input so that the desired coolant temperature can be set. A further flow sensor with an attached control valve controls the cooling water flow and thus the cooling capacity of the double-tube heat exchanger operating on the counter flow principle. The new design of the sample chamber provides various lateral grooves to allow temperature sensors to be attached to the test samples, which have up to twelve drill holes. Local temperature differences are detected just below the channel surface of the sample and are used for later evaluation, cf. ***Figure 5***. It is most likely that layers or corrosion products that form at the measuring points lead to a change in the heat transfer. Gel-like deposits with a high viscosity can also settle due to coolant corrosion and lead to thermal insulation. Coupled with subsequent metallographic investigations, degradation mechanisms can be better described. The co-developed control software allows fully automated operation including pressure and leak testing before the start of the test.

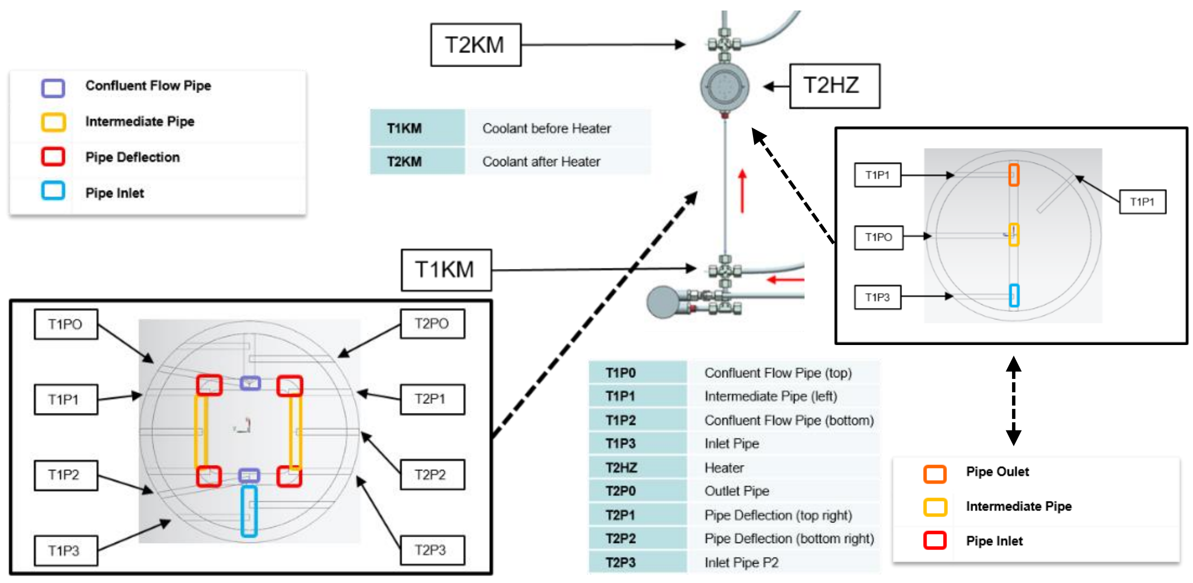


Figure 5: Instrumentation of the FDC Facility; Positioning of thermocouples in water spider (left) and pipe flow (right) sample

3.2 Selected service-oriented Metal Samples

Within a regular cooling system, pipe flows often run in a straight line, deflected, split or confluent. These geometric elementary structures cause different wall shear stresses and forces which act on the adjacent material surfaces and thus change the passivation behavior of the materials in combination with the inhibition concept of the coolant. Samples with a linearly milled flow channel are used for calibration tests and preliminary investigations. The influence of the flow velocity on the erosive corrosive effect on metallic surfaces as a function of pressure and temperature is investigated on these samples with filigree channel guidance of 3.5 mm diameter. Samples of the so-called "Complex Pipe Flow" are planned for future investigations, since this sample geometry reflects real conditions in cooled areas of crankcases in combustion engines, but also in serpentine-like channel flows of battery or fuel cell driven cooling circuit systems, ***Figure 5***.

3.3 Test Parameters for preliminary test

Current investigations are carried out similarly to the recommended test parameters of the FVV guideline R530-2005. The test parameters reflect service-oriented stresses of internal combustion engines and can be adapted. In addition, the data obtained at the FDCF are compared with the MHTA data collected over many years. During the test phase, tests are carried out contrary to the prescribed test duration of 96 h. Only 24 h tests are carried out without rest phases in order to be able to carry out the initial assessment of the influences, since the chemical, very complex and cost-intensive cleaning of the test rig before and after each test is very time-consuming and therefore longer test durations are planned in the future. The test parameters used are listed in ***Table 2***. For further evaluation of the liquid medium used, it is possible to automatically take a sample of the corrosion electrolyte during the test period.

Table 2: *Test parameters of the flow dynamic corrosion apparatus (FDC)*

Test parameters	Unit	Value	Performance Range1,8
Overpressure	bar	2,5 ± 0,1	up to 5,0
Volume flow *(main flow)*	l/min	4,3 ± 0,1	up to 10,0
Heat flux density (aluminum)	W/cm^2	Complex Pipe Flow: 237 ± 10 Straight Pipe Flow 533 ± 10	User-defined
Heat flux density (grey cast iron)	W/cm^2	Water Spider: 277 ± 10 Straight Pipe Flow 622 ± 10	User-defined
Coolant temperature *(deionized water)*	°C	105 ± 0,5	105 ± 0,5
Test duration	h	24	arbitrary

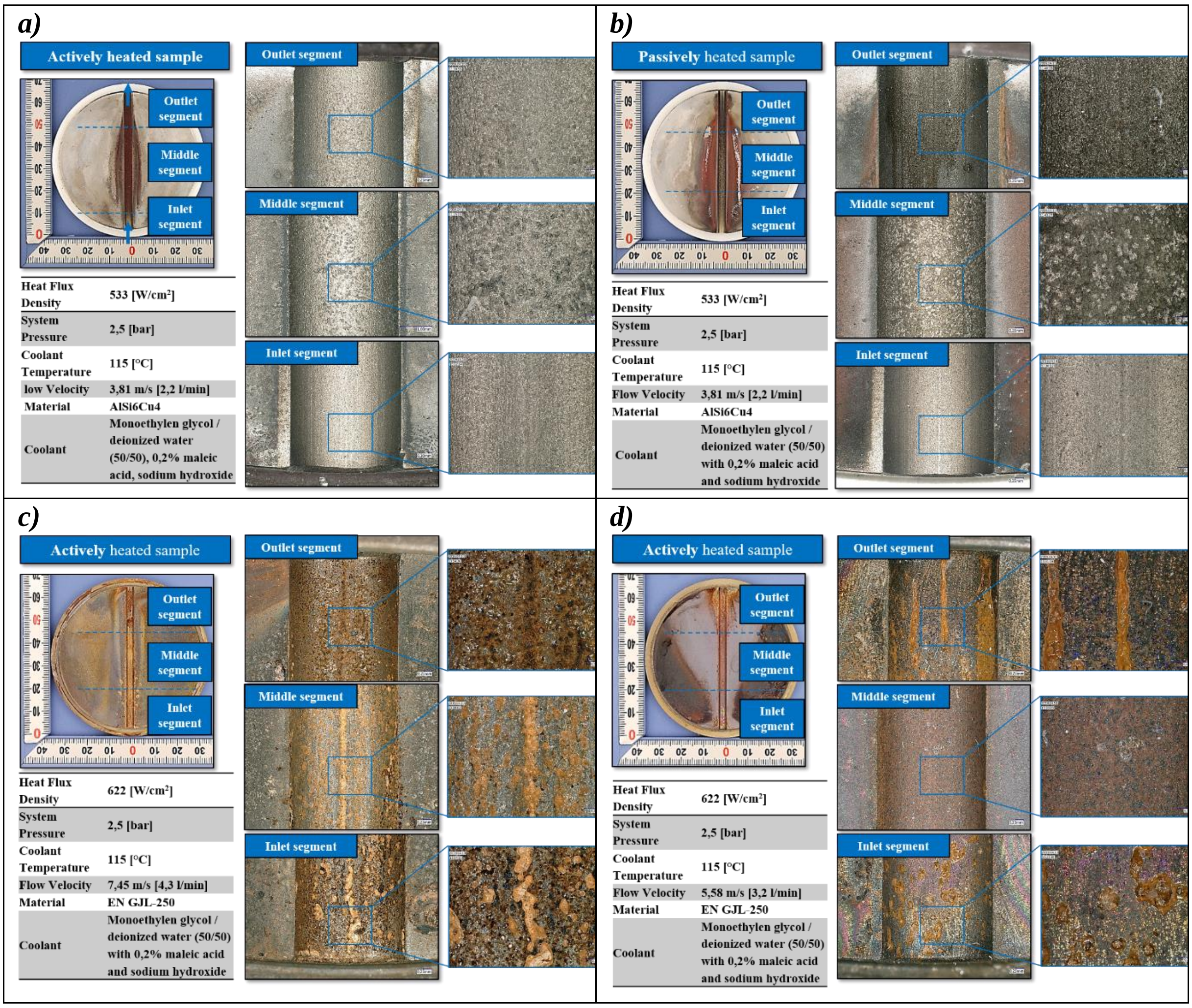
4 Pre-Screening and selected Results

The test rig calibration tests and preliminary tests are based on the standardized test according to the FVV Guideline R530-2005. Due to test rig engineering innovations and the new design, the FDC test rig is used to investigate the three prevailing phenomena of corrosion, cavitation and erosion in flow and heat affected cooling systems and to investigate the mostly superimposed effects individually in order to investigate their dependencies and influences on the underlying materials. In the following, selected results of investigations with non-commercial coolant products are presented. First, a non-inhibited monoethylene glycol-water mixture (MEG/W) is used which is provided with 0.2% maleic acid and sodium hydroxide solution in order to achieve a pH stabilization of 8.2. In the course of the phenomenological investigation of cavitation, erosion and corrosion, the coolant must not have any inhibitors which superimpose the mechanisms and thus become indistinguishable. In addition, the MEG/W is a system which describes a coolant when it has been in use for many years and has used up all inhibitors to passivate cooling surfaces. The basic influencing factors on the fluid dynamic corrosion and degradation behavior of coolant systems are listed in ***Table 3***. For the first time, it has been possible to heat the aluminum and grey cast iron samples to be tested via coordinated thermal management of the FDC system in such a way that, despite the very small transfer surfaces of the channel geometries, the coolant temperatures can be kept constant at 115°C by means of controlled heat exchange principles. The associated problem of the different thermal conductivities of both materials, which leads to different heating rates and maxima of the coolant, is solved by the additional installation of a separate heat source in the sleeve format.

Table 3 : *Possible effects of physical parameters on degradation behavior*

Basic impacting factors	Main of Influences / Presumption
Temperature	- high temperatures promote electrochemical corrosion
Flow rate	- high flow rates promote wall shear stresses (erosion)
Particles	- superimposed erosive impact due to multi-phase flow
Canal geometry	- high influence in terms of pressure losses, flow stalls in canals (cavitation) - abrasive effect due to flow deflections, impingement sections and confluent streams)
Coolant	- simplified, basic inhibited, special adapted
Material	- different materials must be matched to the cooling system in order not to produce counterproductive results from the protective effect of the coolant.

First metallographic results on samples with straight channel guidance show large differences regarding the erosive-corrosive effect of the non-inhibited coolant at different flow velocities. All samples are divided into three zones or segments for evaluation. ***Figure 6 a)*** shows the actively heated sample from AlSi6Cu4 after the test. The reddish coloration across all segments in the channel was analyzed by EDX. Copper precipitates were detected. A quick test with ammonia solution, in which the solution was dripped drop by drop onto the channel section and thus triggered a bluish copper complex formation. The reddish color was lost after drying due to the dissolution of the copper. The actively heated AlSi6Cu4 sample clearly shows that higher outlet temperatures at low flow velocities lead to increased corrosion. The passively heated sample shows significantly less corrosion attack, but increased erosion is visible in the middle and outlet segment, ***Figure 6 b)***. Both samples show little or no degradation at the inlet segment. Compared to the AlSi6Cu4 samples, very strong corrosion attack is visible in the grey cast iron samples, as expected. ***Figure 6 c)*** clearly shows that erosion is the predominant cause of degradation at the beginning of the channel and that corrosion is more visible with increasing channel length and temperature increase of the coolant. If the flow velocity is further increased, the erosive effect in the inlet segment is increased and the corrosion attack is predominantly intensified, ***Figure 6 d)***.



a)

Heat Flux Density	533 [W/cm²]
System Pressure	2,5 [bar]
Coolant Temperature	115 [°C]
low Velocity	3,81 m/s [2,2 l/min]
Material	AlSi6Cu4
Coolant	Monoethylen glycol / deionized water (50/50), 0,2% maleic acid, sodium hydroxide

b)

Heat Flux Density	533 [W/cm²]
System Pressure	2,5 [bar]
Coolant Temperature	115 [°C]
Flow Velocity	3,81 m/s [2,2 l/min]
Material	AlSi6Cu4
Coolant	Monoethylen glycol / deionized water (50/50) with 0,2% maleic acid and sodium hydroxide

c)

Heat Flux Density	622 [W/cm²]
System Pressure	2,5 [bar]
Coolant Temperature	115 [°C]
Flow Velocity	7,45 m/s [4,3 l/min]
Material	EN GJL-250
Coolant	Monoethylen glycol / deionized water (50/50) with 0,2% maleic acid and sodium hydroxide

d)

Heat Flux Density	622 [W/cm²]
System Pressure	2,5 [bar]
Coolant Temperature	115 [°C]
Flow Velocity	5,58 m/s [3,2 l/min]
Material	EN GJL-250
Coolant	Monoethylen glycol / deionized water (50/50) with 0,2% maleic acid and sodium hydroxide

Figure 6: Preliminary results; visual findings of ***a)*** the actively heated AlSi6Cu4 at 3,81 m/s flow velocity; ***b)*** the passively heated AlSi6Cu4 at 3,81 [m/s] flow velocity; ***c)*** the actively heated AlSi6Cu4 at 5,58 [m/s] flow velocity; ***d)*** the actively heated EN GJL-250 at 7,45 [m/s] flow velocity

5 Conclusions and Outlook

The overriding goal of this work was the conceptual design and technical implementation of a test facility for material characterization in coolants in stress scenarios relevant to service. As progress to the already established dynamic test method according to the guideline FVV R530-2005 for material and coolant qualification for cooling systems in internal combustion engines, it was possible for the first time to investigate the degradation phenomena known in cooling systems in a differentiated way. These include in particular erosive stresses due to limited wall shear strengths or an abrasive particle impact, cavitation phenomena in abruptly changing channel geometries and electrochemical, metal-dissolving processes. The developed test items "Pipe Flow" and "Complex Pipe Flow" differ in the channel design and have to be considered differently. In contrast to the "Pipe Flow" sample, the "Complex Pipe Flow " sample has a rectilinear channel inlet that leads into a branch and confluences leads into a likewise rectilinear channel outlet at the top. The deflections are selected on the basis of radii in crank cases that occur in practice. The "pipe flow" sample, on the other hand, is used for a pre-characterization of the turbulent flow in order to investigate interfacial phenomena at the transition from the sample chamber to the sample. In contrast to today's established test methods, the developed FDC Facility has all the technical prerequisites for setting erosive, cavitative and corrosive conditions, which can be considered in a differentiated way. The advantages are the suitability of materials and coolants to be tested with realistic design of cooling channels in order to derive constructive design proposals.

First results on the "Pipe Flow" sample show that there is a mechanism change in the degradation behavior of both AlSi6Cu4 and EN GJL-250. These are boundary flow velocities which have erosive influences on the material surfaces. With increasing mean coolant temperature, electrochemical corrosion predominates. At certain limit temperatures, this leads to formation of boiling bubbles and causes cavitation craters, described in ***chapter 3.1***. At the interface between the active hot sample surface and the coolant, the local temperatures are significantly higher than the mean coolant temperature. This even promotes the aforementioned degradation mechanisms.

In the future, the surface roughness of the test samples will be adapted to the values commonly used in automotive applications in order to investigate the dependence of erosion on the roughness of cast components. At the same time, the test methodology is modified to create a new test cycle, defining the test duration, temperature, pressure, and flow as well as the cold and hot phases in order to obtain results that can be used as design parameters for future cooling systems.

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