EXPERIMENTAL INVESTIGATION OF COKING CHARACTERISTICS OF KEROSENE JET A-1 WITH RESPECT TO PRACTICAL APPLICATIONS

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OVERVIEW

From different previous investigations is known that fuels based on hydrocarbons tend towards partial decomposition at high temperatures. In rocket motors the fuel first has to cool the nozzle wall by flowing through special cooling channels before entering the injector. In the case of hydrocarbon fuels (e.g. kerosene, Methane, Propane) the development of coking deposition (especially carbon) is possible due to the high cooling channel wall temperatures.

Such a coking deposit layer may increase the pressure loss because of a reduction of flow cross-sectional area and roughness effects, by the way combustion chamber pressure as well as power output are reduced too. Furthermore a decrease of cooling efficiency is occurring due to an additional thermal resistance resulting in an increase of hot gas side nozzle wall temperature. To estimate all these effects a simple calculation method of coking behaviour is needed.

Based on a study of literature a large number of influencing parameters on coking characteristics are summarized first. From different publications is known that especially in the case of kerosene a thermal oxidation starts at temperatures higher than 150 °C followed by a pyrolytic decomposition at above 480 °C. Systemising different published experimental results a simple empirical correlation will be introduced.

With respect to practical applications in rocket engines a low cost test facility for qualitative investigations was developed at TU Dresden supported by the Astrium Space Transportation GmbH (Munich). This coking test facility does not enable to determine the quantity (mass, thickness) of carbon deposits but rather its influences on flow and heat transfer characteristics in the test channel. For this reason friction and heat transfer coefficients are measured prior and subsequent to a long duration coking tests using an additional model test facility. Both coking and model test facility are described in the second part of this paper together with the measuring procedure and experimental results.

A third section is dealing with some approximate calculations of the impact of coking layer development on heat transfer and flow characteristics in cooling channels at temperature and pressure parameters close to practical applications in rocket motors. For this purpose the empirical correlation based on the experimental results documented in several publications is used. The present (qualitative) as well as the published (quantitative) experimental investigations together with the results of the calculations confirm that no problems have to be expected due to coking effects in cooling channels even in the case of reusable rocket motors.

NOMENCLATURE

Variables and units

AC	aromatics content	%
k	roughness height	μm
L	length	mm
m	mass	μg
m Nu J	deposition rate (mass flow density) Nusselt number related to diameter	$\mu g/(cm^2 h)$
r [*] R	thermal resistance buildup rate thermal resistance	K m²/(W min) K/W
Re _d	Reynolds number related to diameter	-
t, T	Celsius, Kelvin temperature	°C, K
δ	thickness	μm
λ	heat conductivity	W/(m K)
λ_F	friction coefficient	-
η	dynamic viscosity	Pa s
ρ	density	kg/m³
τ	time	h

Subscripts

air	air
cok	coking layer
k	kerosene (bulk flow)
ref	reference state
W	wall

Some of the units and its prefixes given here correspond to the most usual in the field of coking investigations.

1. BASICS AND INTRODUCTION

At higher temperatures hydrocarbon fuels (e.g. Methane CH_4 , Propane C_3H_8 , kerosene C_nH_m) tend to decompose partially. All investigations described below are focused on kerosene, especially Jet A-1, because kerosene definitely has a special importance with respect to present aircraft engines and seems to have an increasing importance for future rocket engines. Prior to the injection into the combustion chamber of a rocket engine the fuel is used to cool the nozzle wall flowing through special cooling channels. If in the case of hydrocarbon fuels a coking layer should develop at the cooling channel wall the following consequences have to be considered:

change of flow characteristics due to the decrease of cooling channel cross-sectional area and roughness effects
 increase of pressure loss, decrease of chamber pressure (and power output),

 change of heat transfer characteristics due to the development of an additional thermal resistance – decrease of heat transfer rate, increase of hot gas side nozzle wall temperature.

The reliable thermal and fluidic design of rocket motor cooling systems using hydrocarbon fuels as coolant additionally requires – compared to hydrogen – quantitative information concerning coking behaviour. In general it has to be considered that a lot of research projects have dealt with this special field of interest. Nevertheless the results of all these theoretical and experimental investigations have to be evaluated as "not sufficient". Up to today no closed solution or even a validated procedure exists to calculate coking layer effects on pressure drop and heat transfer characteristics.

From a large number of investigations two different mechanisms of hydrocarbon decomposition are known:

- At fuel temperatures above 150 °C a thermal fuel oxidation process starts activated by dissolved oxygen. This oxidation (of course) depends mainly on the mass fraction of dissolved oxygen and probably also on the channel wall material which acts as a catalyst.
- At temperatures above 480 °C a pyrolysis occurs with the result of the decomposition of long hydrocarbon molecules.

With respect to rocket engine parameters fuel temperatures have to be classified in the region of thermal decomposition. As a result of the decomposition processes insoluble components are generated which either can be removed by the bulk flow (bulk fouling) or deposited at the channel wall (surface fouling). The consequences of surface fouling are summarised above whereas bulk fouling also may cause problems especially if coking particles clog small pipes or orifices in the fuel injection system. Finally the composition of the hydrocarbon fuel is changed with possible impact on the combustion behaviour (fuel value).

Summarising the data of several publications the insolubles can be characterised as follows:

- The chemical composition is based on 80 % carbon (C).
- An averaged density of the insolubles is suggested in the range of $400 \le \rho_{cok} \le 800 \text{ kg}/\text{ m}^3$.
- The averaged heat conductivity is given in the literature with $0.19 \le \lambda_{cok} \le 0.95$ W /(mK).

In the following all remarks are focussed on the problem of surface fouling, the deposition of insolubles at the channel or pipe wall due to hydrocarbon decomposition processes. Usually the development of such a coking layer is measured in terms of the mass of deposits per unit area and time (deposition rate)

(1)
$$\hat{\mathbf{m}}_{cok} = \frac{\mathbf{m}_{cok}}{\mathbf{A} \cdot \Delta \tau} \text{ in } \frac{\mu g}{\mathbf{cm}^2 \cdot \mathbf{h}}$$

or in terms of the development of an additional heat conduction resistance per unit time (related to channel surface)

(2)
$$r_{cok}^{*} = \frac{R_{cok} \cdot A}{\Delta \tau} = \frac{(\delta/\lambda)_{cok}}{\Delta \tau}$$
 in $\frac{K \cdot m^{2}}{W \cdot min}$

(called thermal resistance buildup rate).

A large number of different influencing factors on coking could be detected from experimental investigations. Some of the most interesting facts found in the literature are summarised in the following section. Important parameters are

- channel or pipe wall temperature t_w, which depends on the heat transfer conditions (flow character),
- kerosene temperature t_k depending on inlet condition and transferred heat,
- type of wall material which probably acts as a catalyst,
- type of kerosene, especially aromatics and sulphur content,
- dissolved oxygen fraction, respectively.

Not the detailed investigation of all these influencing parameters was the aim of the present project but rather the search for a practicable engineering method to estimate the impact of coking on the operation stability of a cooling system especially for rocket engines based on hydrocarbon fuels.

2. EXPERIMENTAL INVESTIGATIONS

The results of some selected publications should be presented in the following. This choice is geared to the level of interest for engineering purposes as described above. By the way this cannot represent a complete survey on the available literature with respect to the large scientific field of coking.

To investigate the coking behaviour especially of kerosene a standard test apparatus was developed called "Jet Fuel Thermal Oxidizer Tester (JFTOT)", see Rachner¹. A one-way kerosene flow is entering a heated pipe at a supercritical pressure level ($p_k \approx 34.5$ bar). Downstream a filter section (sintered material) is included. Pipe wall temperature as well as filter pressure drop are measured. A first test procedure is realised by holding a constant pipe wall temperature of $t_w = 260$ °C for $\Delta \tau = 2.5$ h. The increase of filter pressure difference due to insoluble coking particles deposited in the pores of the filter material is measured continuously (bulk fouling). Additionally surface fouling can be detected by means of a visual analysis of the inner pipe surface after removing.

A second test procedure is characterised by a stepwise increase of pipe wall temperature up to a significant increase of filter pressure drop. The corresponding wall temperature is called "break point temperature" of the special fuel and remarks the beginning of the thermal deposition processes. Future steadystate fuel operation temperatures should be less than the break point temperature to prevent coking. Numerous publications are available dealing with different aspects of the thermal stability of kerosene especially with respect to gas turbine applications. Most of them were published within the last 15 years. A lot of complex test facilities are described mostly including expensive measuring equipment. All these test facilities are designed to investigate the coking behaviour in special test pipes depending on the influencing parameters summarized above.

In general two measuring procedures are used: the weighing technology comparing the mass of a clean test pipe (or filter) to its mass subsequent to the coking test. Secondly the deposited carbon is oxidised and the mass of the resulting carbon dioxide is measured. Both test procedures require the following steps:

- previous cleaning of the test pipe (rinsing with Methanol and/or ultra sound cleaning and/or vacuum drying),
- determination of the cleaned test pipe mass,
- coking test run(s),
- subsequent cleaning of test pipe (remove remaining fuel, vacuum drying),
- measurement of the carbon deposit mass (weighing) or determination of the carbon dioxide mass after oxidising.

The coking test runs can be divided into groups with respect to pressure and temperature level, kerosene and pipe wall type, character of kerosene flow (one-way, circular flow) and test duration (regarding to gas turbine applications up to 24 hours and longer).



FIG. 1 Deposition rate depending on fuel temperature, wall temperature and aromatics content from Chin et al.² $(p = 1.38 \text{ MPa}, \Delta \tau = 6 \text{ h}, \dot{V}_k = 50 \text{ cm}^3/\text{min})$

Chin et al.² used a heater section similar to the present (see below) including a stainless-steel test pipe (length L = 152 mm, $d_i = 2.15$ mm). Different kerosene types with varying aromatics content (fraction of hydrocarbons based on benzene group) were flowing in the closed-loop test facility with test durations of $\Delta \tau = 6$ up to 22 hours. Wall and kerosene temperatures are varied too. The mass of coking deposits is determined by weighing and the results are plotted as deposition rate \hat{m}_{cok} (Eq. (1)) versus t_w and t_k , respectively.



FIG. 2 Deposition rate (deposited mass) depending on test duration from Chin et al.² and Edwards and Atria³

As shown in Fig. 1 the coking deposition rate increases strongly with fuel and tube wall temperature. Later an averaged reference temperature is suggested which approximates these influences very well. Further the deposition rate slightly depends on the aromatics content, for Jet A-1 a value of AC = 20 % can be assumed. Additionally Chin et al.² present a plot of the deposition rate \hat{m}_{cok} versus test duration (left plot in Fig. 2).

The left plot shows a strongly increasing deposition rate within the first two hours of the test duration followed by a nearly constant value. In the case of a steady-state flow with constant wall and fuel temperatures the deposition rate is expected to be at a nearly constant value, the behaviour up to $\Delta \tau \approx 2$ h is not corresponding to this assumption.

The right plot in Fig. 2 is taken from Edwards and Atria³. In this publication measuring results with different types of kerosene (Jet A, Jet A-1, JPTS, JP-7 – air saturated or deoxygenated) are presented. A long stainless-steel test tube (L = 120 cm, $d_i = 1.4 \text{ mm} - A_i \approx 53 \text{ cm}^2$) is used to detect the dependence of coking behaviour from streamwise position. For this reason the tube is separated subsequent to the test runs (up to $\Delta \tau = 50$ h) and the deposit mass m_{cok} is quantified by carbon oxidation. Some test results are plotted as surface deposition mass versus test duration for different types of kerosene (right plot in Fig. 2). The constant slope of the curves corresponds qualitatively to the results of Chin et al.² (at $\tau \ge 2$ h), but the numerical values of deposition rate are in order of magnitude smaller (calculated example for Jet A-1 presented in Fig. 2). So a qualified comparison of both measurements is not possible.

In a technical report published by Michel⁴ the combustion performance and heat transfer characteristics of hydrocarbon propellants are investigated. The problem of coking behaviour only takes a small part of this report notwithstanding the results are summarized in an interesting plot. The measuring principle is very simple: a hydrocarbon fuel is flowing through a channel (Monel 500) with a constant bulk-flow temperature t_k . The power of an electric heater \dot{Q} is measured as well as the channel wall temperature t_w . In this way the thermal resistance R between bulk flow and wall can be determined. In the case of the development of coking depositions at the wall the thermal resistance increases due to an additional part R_{cok} caused by the heat conduction in the coking layer

(3)
$$(R_{clean} + R_{cok}) = \frac{\dot{Q}}{t_w - t_k}$$

(R_{clean} ... clean pipe condition). Results of the experimental investigations with Propane are visualised as a so-called thermal resistance buildup rate r_{cok}^* (see Eq. (2)) versus temperature t presented in Fig. 3 (here transformed into SI-units, original see also Rousar et al.⁶).



FIG. 3 Coking layer thermal resistance buildup rate versus temperature for Propane and kerosene RP-1

The measured data show as expected an increase of the thermal resistance buildup rate with higher temperatures, but a strong scattering of the measurements has to be stated. In Michel⁴ the used temperature is not specified (wall or bulk flow), so it is taken as an averaged temperature. Additional to the measuring results of Propane a curve valid for kerosene RP-1 (taken from Wagner and Soji⁵) is included which corresponds very well to the averaged Propane data. The plot of thermal resistance buildup rate seems to be very helpful with respect to thermal design of cooling devices, for this reason all experimental results are summarised in this manner within the next section.

Information about the pyrolytic decomposition of hydrocarbon fuels are given in the publication of Wohlwendt et al.⁷. A non-flow micro reactor with adjustable temperature, pressure and duration time is used to investigate the thermal stability of the following deoxygenated fuels (prevention of thermal oxidation): kerosene RP-1, JP-10 and quadricyclane. The measurements are carried at high pressures and temperatures. A plot of remaining fuel versus temperature shows that pyrolytic decomposition of RP-1 and JP-10 starts in the range of $t_k \ge 450$ °C which agrees to the statement given above.



FIG. 4 Averaged values of deposition rate depending on kerosene and tube wall type (from Stiegemeier et al.⁸)

Stiegemeier et al.⁸ present experimental results from a complex test facility which was designed to realise parameters in the range of rocket engine cooling applications ($p_k \approx 70$ bar). Stainless-steel or copper test pipes ($d_i = 1.52 \text{ mm}$) are included in a closed-loop test facility with flow of different kerosene types at temperatures $t_k \le 260$ °C and 400 °C $\le t_w \le 540$ °C. The mass of deposited carbon is measured in terms of the carbon dioxide mass after oxidation. Some selected measurements are shown in Fig. 4, the deposition rates are averaged between different flow velocities and plotted for varying kerosene types and test pipe wall materials. Comparing these measurements to the results of Chin et al.² (Fig. 1) gives a good agreement at low fuel temperatures ($T_k \leq 500$ K) for stainless-steel tubes ($\dot{m}_{cok} \approx 50 \dots 75 \ \mu g/(cm^2 h)$). From Fig. 4 also a significant influence of wall material is derived, copper acts as a catalyst with the result of an acceleration of the decomposition process.

This survey on publications dealing with the coking behaviour of hydrocarbon is closed – without any right to completeness – introducing the experimental results of Linne et al.⁹. These data are of special interest because of the very high wall temperatures ($t_w \le 930$ °C). The test facility is similar to Stiegemeier et al.⁸ (closed-loop, kerosene JP-7, $p_k \approx 70$ bar,

 $d_i = 3.18$ mm, L = 355 mm, CO₂-measurement). Experimental results are plotted partially as carbon deposition density \hat{m}_{cok} (in µg/cm²) versus tube distance (see Fig. 5). A strong dependence of carbon deposition from streamwise position is visible (red line). To use this data for later evaluation an averaged coking deposition density at the inner tube surface ($\hat{m}_{cok} \approx 400 \ \mu g/cm^2$, dotted line) is related to the test duration ($\Delta \tau \approx 10^3$ s) to get the averaged deposition rate of $\hat{m}_{cok} \approx 1440 \ \mu g/(cm^2 h)$.



FIG. 5 Streamwise dependence of coking deposition density of JP-7 (from Linne et al.⁹)

The list of publications dealing with different aspects of decomposition of hydrocarbon fuels could be continued. Further information about several impacts are documented e.g. in Jones et al.¹⁰, Hernandez and Mercer¹¹, Kauffmann¹² and Heneghan et al.¹³, respectively. Summarising it has to be stated that a large number of influencing parameters on the coking behaviour of hydrocarbon fuels exist. With respect to engineering purposes a simple method for an approximate quantification is needed to estimate the consequences of especially coking depositions (surface fouling) on heat transfer and flow characteristics in cooling channels. A first step is to be presented in the following section.

3. NUMERICAL ESTIMATION OF COKING DEPOSITION

Based on the data plot in terms of the coking thermal resistance development rate r_{cok}^* versus temperature (shown in Fig. 3) an adequate presentation is developed including some experimental results of other authors for comparison. The main purpose is to derive a simple empirical correlation which describes the impact of coking depositions on heat transfer and, if possible, on pressure loss. For this reason first a qualified reference temperature has to be defined considering bulk flow as well as wall temperature. In the case of turbulent flows, for instance with respect to convective heat transfer calculations, a reference temperature

(4)
$$T_{ref} = T_k + \frac{1}{3}(T_w - T_k)$$

is suggested, this temperature also is tried to use here. Secondly the results plotted as $\hat{\vec{m}}_{cok}$ versus T have to be transformed into r_{cok}^* versus T data. Considering the definitions Eq. (1) and

(2) this transformation will be possible assuming an averaged density of coking deposits of $\rho_{cok}\approx 600~kg/m^3$ and a heat conductivity of $\lambda_{cok}\approx 0.6~W/(m~K)$ – see above.

(5)
$$\hat{m}_{cok} = \frac{(\rho \cdot A \cdot \delta)_{cok}}{A \cdot \Delta \tau} \rightarrow \frac{\hat{m}_{cok}}{(\rho \cdot \lambda)_{cok}} = r_{cok}^* = \frac{(\delta/\lambda)_{cok}}{\Delta \tau}$$

Using this approximated properties together with Eq. (5) the experimental data of Michel⁴ and Wagner and Shoji⁵ (r_{cok}^* - data, see Fig. 3) can be plotted together with results of Chin et al.² (see Fig. 1), Stiegemeier et al.⁸ (see Fig. 4), Linne et. al.⁹ (see Fig. 5) and Jones et al.¹⁰, all \hat{m}_{cok} - data, as presented in Fig. 6.



FIG. 6 Thermal resistance buildup rate versus reference temperature (data of different authors)

The shape of the red symbols in Fig. 6 is attached to the results of different authors as remarked in the legend. The scattering of the data is considerable even in the case of using the reference temperature Eq. (4), but it strongly increases if T_{ref} is replaced by the wall temperature T_w (compare unfilled grey symbols).

To estimate the thermal resistance buildup rate numerically an empirical correlation is created

(6)
$$\frac{\mathbf{r}_{cok}^*}{(\mathbf{m}^2 \cdot \mathbf{K})/(\mathbf{W} \cdot \min)} = \mathbf{A} \cdot \exp\left[\frac{\mathbf{B}}{(\mathbf{T}_{ref} / \mathbf{K})^2}\right]$$

(constants $A = 5.5 \cdot 10^{-5}$, $B = -2.7 \cdot 10^{6}$) and plotted as black line in Fig. 6. By means of Eq. (6) the following influences of coking depositions on heat transfer and pressure loss can be estimated approximately:

- the development of an additional thermal resistance due to a coking layer depending on fluid and wall temperature as well as duration time,
- the increase of the coking layer thickness δ_{cok} using the transformation in Eq. (5) in inverse direction. From this layer thickness the decrease of flow channel cross-sectional area and the corresponding increase of flow velocity and pressure loss are calculable.

Summarising it has to be remembered that Eq. (6) only allows an approximation of coking behaviour for engineering purposes independent of kerosene (hydrocarbon) type, flow channel wall material and other influencing parameters.

4. PRESENT TEST FACILITIES

The motivation to create the test facilities described below was caused in the absence of qualified methods of determining the coking behaviour of hydrocarbon fuels. For better understanding of this motivation with respect to the results presented in Fig. 6 and Eq. (6) it has to be noted that the iterative process of designing the test facilities and the study of literature were executed simultaneously within the last years.

First the coking test facility was developed to investigate the coking behaviour of kerosene only qualitatively because the measuring technique to determine the mass of coking deposits in the range of milligrams is very expensive. Later a quantitative investigation method was added not by means of measuring the carbon mass but by determining the influences of coking deposits on heat transfer and pressure loss in the test pipe. For this purpose an additional special model test facility was created.

4.1. Coking test facility

The development of the coking test facility was carried out considering some important requirements:

- use of kerosene flowing through a heated test pipe at wall temperatures up to $t_w = 400$ °C and pressures greater than the kerosene saturation pressure $p_k > p_{k,sat}(t_w)$ to prevent subcooled boiling at the test pipe wall,
- realisation of a defined test duration $\Delta \tau \leq 30$ min, that especially means no kerosene contamination of the test pipe in the pre-heating phase as well as while cooling down subsequent to the test,
- guarantee of (nearly) constant flow conditions and pipe wall temperature for each single test,
- compliance with all safety instructions with regard to the high flammability of kerosene-air mixtures (in the case of possible leakages).



FIG. 7 Coking test facility (small picture: installed in the vacuum test chamber)

In the following the coking test facility (Fig. 7 incl. numbering) and the corresponding test procedure are described in a short manner. The upper reservoir (1) first is filled with $V_k = 8 l$ of kerosene (Jet A-1) while the magnetic valve (2) is closed. A cleaned test pipe is installed in the heater section (3) which is partially masked in Fig. 7 – details see Fig. 8. The test facility is completed by an adjustable valve (4) to generate a pressure loss and last but not least the lower kerosene reservoir (5). After combining all components the test facility is installed inside of a large vacuum tank (small picture). Flexible tubes are connected to the upper as well as lower reservoir to pressurise the system with nitrogen (6) up to system pressures of $p_k = 25$ bar.

Fig. 8 shows details of the heater section. The test pipe (copper, $d_i = 5 \text{ mm}$, L = 150 mm (total) / 100 mm (heated)) is clamped between two heater blocks (each supplied with heater cartridges, totally 800 W) using a graphite layer to allow thermal expansion and to ensure good heat conductivity. In Fig. 8 the mounted (without heater cartridges) and dismounted heater section is presented as well as its installation in the test facility.



FIG. 8 Heater section including test pipe, in a mounted and dismounted condition as well as finally installed

Temperatures are measured at the positions marked in Fig. 8: kerosene inlet upstream of heater (A) and outlet downstream of the heater section (C), test pipe wall (B) and kerosene reservoir temperatures. The heater construction principle was modified several times, some detailed information about the reasons are given below together with presentation of experimental results.

After positioning the coking test facility in the vacuum tank the following steps complete the procedure:

- The vacuum tank is evacuated first to minimise heat losses from the heater surface (only radiation) and second to prevent the ignition of kerosene in the case of a leakage due to the absence of oxygen in the surroundings.
- The system is pressurised and the (dry) test pipe is preheated up to the present wall temperature t_w.
- After opening the magnetic valve a kerosene flow driven by a gravitational force is developing, the test duration is variable by adjusting the manual valve (4) (see Fig. 7), the heating power is controlled automatically to get a constant wall temperature even in the case of kerosene flow.
- After the test run the heater is turned off, system pressure is decreased and the test pipe is dismantled.

Fig. 9 shows a plot of the measured temperature data with a wall temperature of $t_w = 350$ °C, an averaged fuel temperature of $t_k \approx 75$ °C and a test duration of $\Delta \tau = 32$ min (initial and final time are detectable from t_k measurement). This special test run used a test pipe divided into two parts so that a visual check of the inner pipe surface was possible without the necessity of any cutting-off process. Photographs showing a view at the inner surface of the copper test pipe prior and subsequent to the test run are added to Fig. 9. These test tubes are supplied with an outer thread to optimise heat conduction and to seal both parts of the pipe against each other.



FIG. 9 Temperature plot of a special test run completed with photographs of the test pipe inner surface

In the test pipe photographs some coking (carbon) deposits are visible having a consistency similar to soot. There is only a very thin coking layer and some single particles which are assumed to have no remarkable influence on heat transfer and pressure loss in the test tube.

To get more detailed information with respect to engineering applications and because of leakage problems with divided test pipes the heater section was rearranged later as documented in Fig. 8 (undivided test pipe, no thread). Additionally a model test facility was developed to measure test pipe heat transfer and friction conditions prior and subsequent to the coking tests.

4.2. Model test facility

The model test facility was designed to compare heat transfer and flow characteristics in a clean test pipe to those in the case of an existing coking layer. For this reason the complete heater section is implemented in a model test apparatus which uses air as fluid (see Fig. 10). The heater section is installed between two mountings (1) made of laminated paper. The air – provided by a mass flow controller – enters the test pipe after passing an inlet temperature and static pressure measurement (wall hole) included in mounting (1).

Heat transfer to the flow is realised using the original heater cartridges (2) connected with a power supply (P_{el}), the pipe wall temperature t_w is measured triple. Additionally a screen (3) is installed and heated at the same wall temperature to minimise conductive as well as radiative heat losses. After leaving the test section the air static pressure and the outlet temperature are measured again. To average the temperature profile which exists in the fluid three special thermocouples are used positioned at different radiuses (4).

Because flow and heating conditions are not necessarily reproducible the transformation of measured data in universal dimensionless terms is recommended.



FIG. 10 Model test facility with included heater section (opened, detail: outlet temperature measurement)

In the case of the flow characteristics the friction coefficient λ_F is determined from the measured static pressure difference (based on flow velocity u)

(7)
$$\lambda_{\rm F} = \frac{p_{\rm air}^{\rm air} - p_{\rm air}^{\rm air}}{\frac{L}{d_{\rm i}} \cdot \frac{\rho}{2} u^2} \quad \text{with} \quad u = \frac{m_{\rm air}}{\rho \cdot \frac{\pi}{4} d_{\rm i}^2} \; .$$

The heat transfer characteristics can be described by means of the Nusselt number Nu_d which is calculated from the energy balance considering convective heat transfer between wall and fluid and increase of fluid enthalpy

(8)
$$\operatorname{Nu}_{d} = \frac{\dot{m}_{air} c_{p,air} (T_{air}^{out} - T_{air}^{in})}{\pi d_{i} L \cdot \Delta T_{av}} \cdot \frac{d_{i}}{\lambda}$$

 ΔT_{av} represents an averaged logarithmic temperature difference between fluid and wall as commonly used for channel flow.

The test procedure is now adapted: First the clean test pipe is included in the model test apparatus (complete heater section), Nu_d and λ_F are measured for varying air mass flow rates and heating power and plotted versus pipe flow Reynolds number $Re_d = \rho u d_i / \eta$. After carrying the coking test (see above) the complete heater section is installed again in the model test facility and all measurements are repeated. A comparison of the measuring results gives information about the influence of possible coking depositions on the friction (pressure loss) and heat transfer characteristics.

5. LONG DURATION TEST

As part of a large number of coking tests using different types of heater configurations also some long duration were executed. These tests are geared to coking problems with respect to practical applications of rocket engines. The total operation time of present rocket motors is limited mostly to less than one hour due to the fact that these engines are used in one-way launcher vehicles. Future types of rocket motors based on hydrocarbon fuels should be qualified to work in re-usable launchers with significant longer operation times. But differing from aircraft engines or gas turbines the operation time of a single mission will be not in the range of hours but of minutes.

For this reason the long duration test was carried – of course also considering the operation mode of the coking test facility – as summarised in the following table:

test pipe	copper, $d_i = 5 \text{ mm}$, $L = 100 \text{ mm}$
wall temperature	$t_w = 400 \circ C \rightarrow p_k \approx 22 \text{ bar}$
fluid	kerosene Jet A-1
fluid temperatures	inlet $t_k \approx 40$ °C, outlet $t_k \approx 150$ °C
single test duration	$\Delta \tau \approx 30 \dots 35 \min$
number of test runs	10 (one test run per day)

The kerosene was pre-heated in the upper reservoir to nearly $t_k \approx 40$ °C by means of a heater mat installed at the outer reservoir surface to ensure a constant test pipe wall temperature of $t_w = 400$ °C (heating power limited to overall 800 W). The procedure of each single test was executed as described above. Subsequent to the test run the heater section was cooled down and the lower reservoir was emptied, the upper reservoir was refilled with kerosene and the next test run started.

Heat transfer and friction characteristics in the test pipe were investigated experimentally using the model test facility prior (clean pipe) and subsequent to the complete coking test series. The results of friction measurements are plotted in Fig. 11 in terms of friction coefficient λ_F versus Reynolds number Re_d.



FIG. 11 Friction coefficients in the test pipe with air flow prior and subsequent to the coking test

The measured data clearly show the transition from the laminar to turbulent flow characteristics. Additionally a difference of friction coefficients prior (red) and subsequent (black) to the long duration coking test is visible. Friction and pressure loss are slightly increasing. At Reynolds numbers $\text{Re}_d \leq 2300$ the empirical equation $\lambda_F = 64/\text{Re}_d$ valid for laminar flow fits the data very well (red line). For turbulent flow the correlation

(9)
$$\frac{\lambda_{\rm F}}{4} = \left[3.48 - 1.7372 \cdot \ln\left(\frac{2\,k}{d_{\rm i}} + \frac{9.35}{{\rm Re}_{\rm d}\sqrt{\lambda_{\rm F}/4}}\right) \right]$$

is introduced which also considers the influence of roughness effects by means of the roughness height k (red line).

The red line plotted in the turbulent region at Reynolds numbers $\text{Re}_d \ge 2300$ corresponds to Eq. (10) with a roughness height of k = 0 in the case of a smooth wall. There exists only a moderate agreement between measurements and theory but it has to be considered that Eq. (9) is valid for fully developed turbulent pipe flow ($\text{Re}_d \ge 7000$). The differences between measuring results prior and subsequent to the coking test can be described by means of Eq. (9) if a roughness height of $k = 10 \ \mu\text{m}$ is introduced (black line). In general the averaged increase of λ_F during the long duration test is in the range of 5 %.

With respect to the convective heat transfer the results of the measurements are visualised in Fig. 12 in terms of the Nusselt number versus Reynolds number.



FIG. 12 Nusselt numbers (heat transfer coefficients) in the test pipe with air flow prior and subsequent to the test

In the range of laminar flow no measurements were possible. The Nusselt numbers shown in Fig. 12 are nearly similar prior and subsequent to the coking test. The curves correspond to well known empirical equations valid for turbulent channel flow:

(10)
$$\operatorname{Nu}_{d} = 0.0235 \cdot (\operatorname{Re}_{d}^{0.8} - 230) \cdot (1.8 \operatorname{Pr}^{0.3} - 0.8) \cdot \mathrm{K}_{\mathrm{in}}$$

and

(11)
$$Nu_{d} = \frac{(Re_{d} - 1000) \cdot Pr \cdot \lambda_{F} / 8}{1 + 12.7 (Pr^{2/3} - 1) \cdot \sqrt{\lambda_{F} / 8}} \cdot K_{in}$$

with an inlet path correction factor of $K_{in} = 1 + (d_i / L)^{2/3}$ and the pipe friction coefficient λ_F from e.g. Eq. (9). The empirical equations differ from each other while the measured values are positioned in between. It seems to be very interesting that heat transfer slightly increases due to the coking depositions (averaged in the range of 2.5 %) which also can be caused by the roughness effects.

Summarizing it has to be stated at this point that even in the case of a long duration coking test only small influences on pressure loss and heat transfer could be detected. Due to the deposition of single carbon particles at the inner pipe surface an additional roughness is developing. In consequence of this roughness the friction as well as heat transfer coefficients slightly increase.

The present measurements cannot be compared to Eq. (6) because this equation firstly bases on the assumption of a closed coking layer with a measurable thickness (which couldn't be detected) and secondly it doesn't include any roughness effects of single carbon particles.

6. SOME CALCULATED RESULTS WITH RESPECT TO PRACTICAL APPLICATIONS

The purpose of these calculations is to investigate the possible influences of coking depositions on heat transfer and pressure loss in cooling channels of a real rocket engine configuration based on the thermal resistance buildup rate definition given from Eq. (6).

Fig. 13 shows a simplified scheme of the thrust chamber nozzle wall and cooling channel configuration which has been used for the present calculations. Special geometrical data like the nozzle contour, local cooling channel width and height and nozzle wall thickness, respectively, as well as kerosene inlet and combustion chamber total conditions (coolant and hot gas mass transfer rate, pressure, temperature) were provided by the customer.



FIG. 13 Simplified scheme of the nozzle and cooling channel geometry used for present calculations

During the calculations the following main steps were executed to get the desired information:

- The nozzle is divided into streamwise steps ∆x (see lower part of Fig. 13), further hot gas pressure and temperature distributions (assuming isentropic expansion) as well as local hot gas side heat transfer coefficients (see (3) in Fig. 13) are determined using the modified Bartz equation (e.g. see Meinert¹⁴).
- In the cooling channel (cross-sectional scheme, upper part of Fig. 13) also pressure loss (channel flow) and heat transfer coefficients (see (4) in Fig. 13) are calculated.
- Further the heat flux \dot{Q}_w is determined from a heat transfer analysis using thermal resistances and considering cooling channel by means of the fin theory (assuming an adiabatic upper channel wall, see (2) in Fig. 13). Now the streamwise coolant (Jet A-1) temperature distribution is resulting from a segmental energy balance. Different wall temperatures are determined from the heat transfer conditions considering differences between channel bottom and side walls (2d heat conduction effects, from detailed CFD analysis).
- With known local wall and fluid temperatures the thermal resistance buildup rate r_{cok}^* is calculated using Eq. (6). For a time interval $\Delta \tau$ the deposited carbon mass is estimated

from Eq. (5) and transferred into a coking layer thickness (see (1) in Fig. 13). For intervals of $\Delta \tau = 30$ min all steps are repeated considering the coking layer developed during the previous time interval.

These calculations deliver a lot of interesting facts about the coking behaviour and its consequences in cooling channels of rocket engines based on hydrocarbon fuels. A general statement seems to be that no special problems with respect to coking have to be expected even in the case of 10 operation periods (each $\Delta \tau = 30$ min) for a rocket motor. For the used set of input data as well as the nozzle and cooling channel configuration and assuming a coking layer development as calculated from Eq. (5) and (6) the total streamwise pressure loss is increasing in the range of less than 1 % (only due to the decrease of flow cross-sectional area, no roughness effects). The hot gas side nozzle wall temperature (throat) increases in the range of 1 %.

Assuming a coking layer development rate 100 times higher than determined from Eq. (5) and (6) the change of hot gas side wall temperature is in the range of 10 % and coolant pressure loss at nearly 1 %, respectively.



FIG. 14 Change of coking layer development rate depending on operation time in the nozzle throat

An additional fact has to be considered: Due to the developing coking layer and its increasing thermal resistance the cooling channel wall temperature decreases. By the way the thermal resistance development rate decreases too and so the coking process is decelerated. Fig. 14 shows the change of coking layer thickness buildup rate versus operation time. The plotted curve emphasises the self-decelerating effect.

7. SUMMARY

As result of a detailed study of literature a large number of different influencing parameters on coking characteristics of hydrocarbon fuels (e.g. kerosene) are known. With respect to engineering applications in the field of rocket motor cooling technology coking seems to have only a very small importance because of the short operation cycles compared to aircraft engines or gas turbines. This statement is supported by the results of present experimental investigations which focussed on practical test conditions. By means of a coking test facility and a model test apparatus no remarkable consequences of coking on heat transfer and pressure loss were detected.

8. ACKNOWLEDGEMENT

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