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EXPERIMENTAL RESULTS WITH NOVEL PLASMA COATED TUBES IN COMPACT TUBE BUNDLES

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ABSTRACT

Boiling heat transfer of R-134a on a porous, plasma coated tube bundle was investigated experimentally to determine the effects of the number of tube rows and the total tube number. The bundle consists of up to 4 tubes with a pitch-to-diameter-ratio of 1.33. Heat transfer coefficients for a single tube with porous copper coating were up to four times higher than for a smooth tube. Observations showed that the plasma coating enhanced the heat transfer coefficient also in tube bundles. The bundle factor of the coated tube bundle showed a similar, slightly increased, trend as the smooth tube bundles. The enhancement effect of the coated tubes decreases to a certain extent with increasing heat flux and decreasing saturation temperature. However, it is significantly less pronounced than trends which have been reported from other investigations. The aim of a stable enhanced coating was confirmed by long-term experiments with steady results.

INTRODUCTION

Heat exchangers with vapor/liquid phase change, such as flooded evaporators, represent major components in the chemical and process industry. Significant effort is directed to improve heat transfer behavior and to investigate advanced structure materials and boiler design. During the last years, the majority of investigations were dealing with advanced coatings applied to small plates or single tubes and only little information is available about the thermo-hydraulic behavior in tube bundles. Furthermore, insights on the long-term stability of coated tubes in tube bundles under several mass flows are completely missing, to-date.

Using HF Plasma Spraying Technology at DLR, research activities are directed towards developing advanced coatings for tubular and plane surfaces of various substrate materials. Following the successful development of stable metal and metal oxide coatings with this technology for boiling experiments, a large variety of specially tailored matrix materials for evaporator and condenser surfaces are feasible. Boiling experiments at DLR with single, copper-coated tubes have shown promising results with a layer thickness of 170 µm, a mean pore size of 41 µm and a porosity of about 20%.

To extend these findings to tube bundles, a test facility has been designed and constructed in the DLR Institute of Technical Thermodynamics that allows experimental investigation of evaporation and condensation on enhanced tubes and tube bundles under a wide range of operation conditions. The main operating parameters of the test facility are: working fluid R134a, pressure between 1 to 25 bar, temperature range of -40 to +100 °C, mass flow rates of 10 to 1000 kg/h and heat fluxes up to 150 kW/m² for a maximum heat duty of 50 kW, with oil flowing inside a tube as heating source.

To compare the boiling behavior on single tubes with that in tube bundle arrangements, a test evaporator has been assembled consisting of up to 24 tubes with a tube length between 30 and 70cm.

In several experiments plasma coated tubes of 350 mm length showed high enhancement factors.. Temperature measurements indicate that the present coated tubes have significant influence on local and average heat transfer coefficients in the tested tube bundle arrangement.

From the results obtained to-date, the pool boiling behavior of coated single tubes in tube bundles with several vertical and horizontal arrangements will be discussed.

EXPERIMENTAL SET-UP

The highly accurate test apparatus has been designed and constructed in the Institute for Technical Thermodynamics of the German Aerospace Center in Stuttgart, Germany. Refrigerant R-134a (CF_3-CH_2F) was used as working fluid. The critical temperature (T_C) and the critical pressure (P_C) of R-134a are 101ºC and 4059 kPa, respectively. The cylindrical test tubes with 18 mm OD and 350 mm length were placed horizontally in the liquid pool. The thermo-oil Therminol D12, flowing inside the 16 mm ID tubes, was used in a temperature range of -40°C to + 90°C as heating medium. The temperature of the liquid R-134a was measured below, above and beside each test tube, and 5 mm from the inlet and outlet with PT100 resistance thermometers with a diameter of 2 mm. The temperature of the vapor was measured in the upper section of the shell with 4 PT100 at the inlet and the outlet. The temperature of the oil at each tube inlet and outlet was measured with a PT100, 5 mm from the end of each tube.

The refrigerant vapor was condensed in a plate condenser, and the condensed liquid returned to a tank where the system pressure was controlled via a heater and was measured by a pressure transducer. Furthermore, four highly accurate pressure transducers were installed at each connection of the shell and tube evaporator for pressure loss measurement. A frequency controlled pump was set to deliver as much liquid out of the tank to achieve a constant liquid level height of 60 mm above the center of the upper test tube. Details of the test tubes are shown in Fig. 1.

The heat flux (q) was varied by oil mass flow rates from 2 000 to 12 000 kg/h in the range from 2 to 100 kW/m^2 for saturations temperatures of -20,-10, 0, 10 and 20°C. Generally, there is an effect on pool boiling heat transfer performance of heating procedure, i.e. with increasing or decreasing heat flux. For consistency, all data were measured with decreasing heat flux, starting at a maximum heat flux of nearly 100 kW/m².

SPECIFICATION OF COATED SURFACES

Due to the influence of coating parameters on the boiling enhancement, surfaces used in this study were analyzed with a Scanning Electron Microscope (SEM), two porosity measurement systems and a contact roughness measuring system, directly after the coating process and also after the heat transfer experiments.

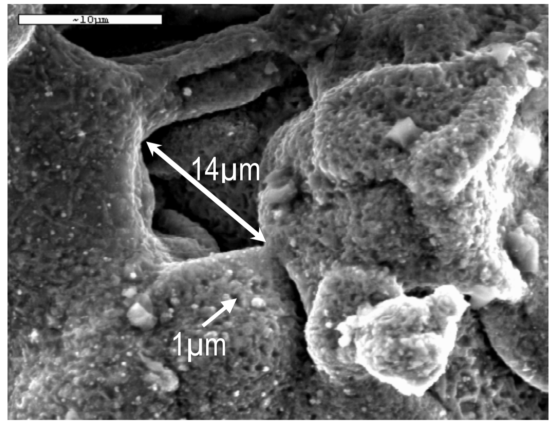


Figure 2: SEM picture of the Copper coating 3500:1

Substantial progress has been made in understanding nucleate boiling heat transfer on smooth tubes and tube bundles. Many researchers (Gorenflo, 1997; Luke, 1997; Zhou, 1997) investigated the effect of surface roughness R_a on the heat transfer and generally found that rougher surfaces enhance the heat transfer. In this study each tubes was measured at four different radial positions with a Hommel Tester T800. The results show a very homogenous roughness R_a of 0.37 µm over the whole surface.

Chien and Webb (1996) reported that nucleate boiling heat transfer on porous surfaces is dominated by the pore structure and its pore size distribution.

The analysis of the porosity by Hg-porosimetry with Thermo-Electron Corporation Pascal 140 and 240 depicted a wide pore size distribution from 0.03 µm to 65 µm, with a mean volume fraction based pore size of 41 µm and an open porosity of nearly 20%.

Typical results of the SEM examination of the surface image of a copper-coated tube are illustrated in Figs. 2 and 3, respectively.

The surface is quite homogenous, consisting of smaller and larger pores due to the wide particle size distribution of the copper powder used in the plasma coating process.

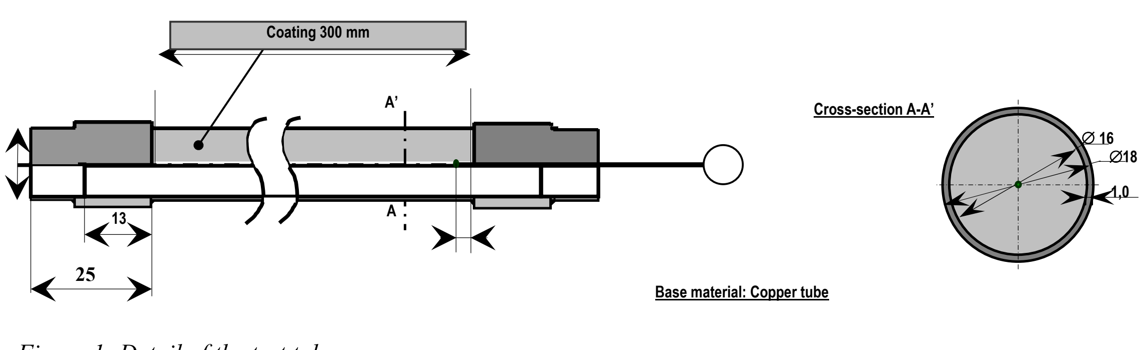


Figure 1: Detail of the test tube

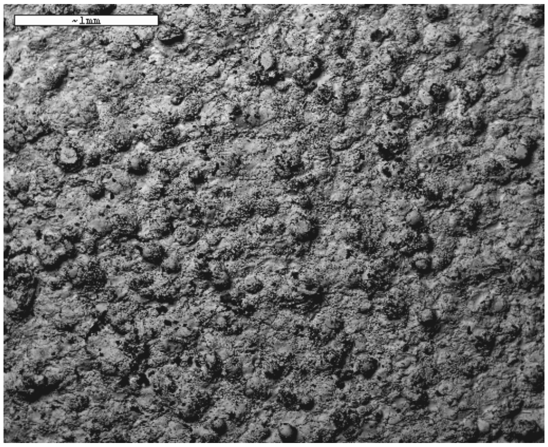


Figure 3: SEM picture of the Copper coating 35:1

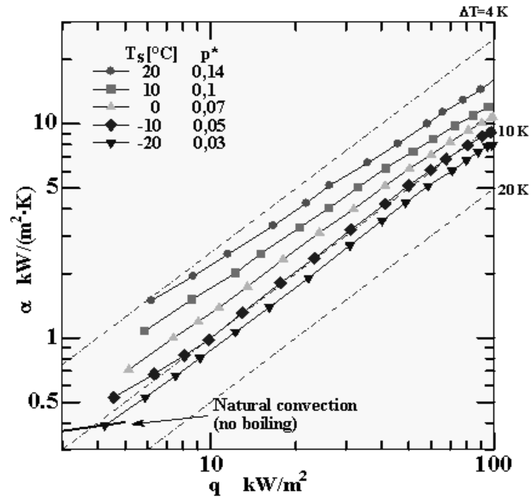


Figure 4: Boiling heat transfer coefficient on one smooth tube (Effect of pressure)

EXPERIMENTAL RESULTS AND DISCUSSION

Single tube results

The heat transfer coefficients of R134a on a smooth reference tube show a well-known behaviour. The heat transfer increases with increasing saturation temperature and increasing heat flux as shown in Fig. 4. The experimental values agree well with the correlation of Gorenflo in the VDI Wärmeatlas (1997).

Figure 5 shows the heat transfer coefficient on a single, copper-coated tube. The experimentally obtained data parallel, with an enhancement of up to 4 times at lower heat fluxes, the smooth data with a slightly flatter trend with increasing heat flux.

The copper coating in the present work delivers, in comparison to former experiments by Yang (2003) and Hsieh (1997), a substantial enhancement at higher heat fluxes, as seen in Fig. 6. The single tube measured by Yang follows the same trend as mentioned by Asano et al. (2003) in their work for thicker coatings, while there seems to be only few potential nucleation sites in the tube of Hsieh due to its low porosity.

The significant factor for future use in a commercial shell and tube evaporator of plasma coated tubes is the stability on the tube surfaces. To-date, only few experiments have been published on this subject. In the present study, long-term experiments have been performed with increasing and decreasing heat flux in the range of 1-120 kW/m² at daily changing saturation temperatures and different mass fluxes as well as driving temperatures. Each tube was replaced monthly and stored in a box permeable to air, and re-installed about one month later. The storage time had no measurable effect on

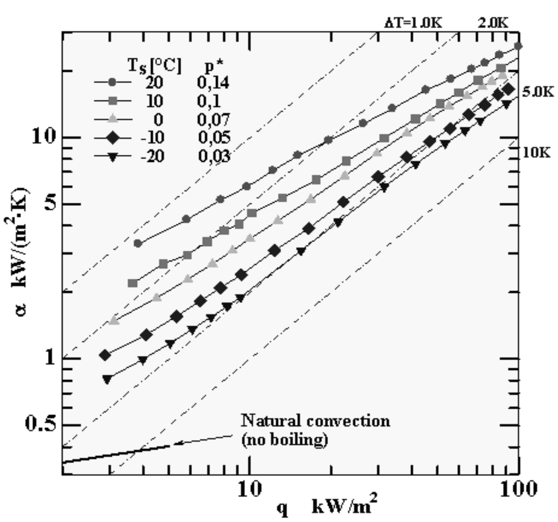


Figure 5: Boiling heat transfer coefficient on one coated tube (Effect of pressure)

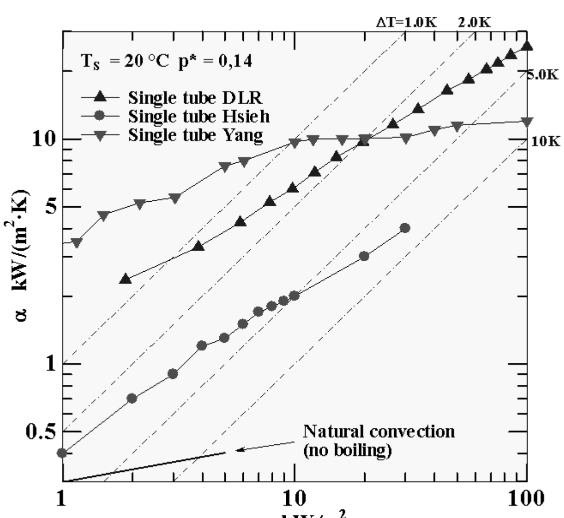


Figure 6: Boiling heat transfer on several porous coated tubes in the literature

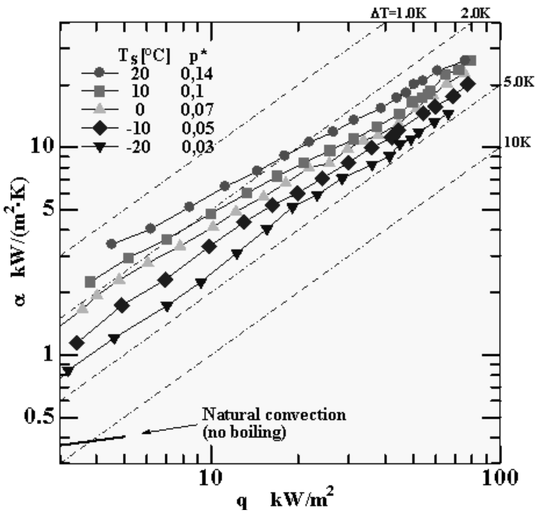


Figure 7: Heat transfer on the upper of two tubes

the heat transfer coefficient. For the presently realised operating time of 3600 h for four coated tubes, the average heat transfer coefficients decreased by only 5%, as compared to the initial values.

Tube bundle results

Experiments on tube bundles with enhanced tubes in in-line arrangement were carried out to investigate the influence of two-phase flow occurring inside the bundle on the heat transfer from the individual tubes.

It is well known that the boiling behaviour of a tube bundle is different from that of a single tube. First of all, the heat transfer at the top of the bundle was found to be significantly higher than on the bottom due to turbulences created by the bubbles rising from the lower tubes. It was observed further that the higher mass inventory of larger bundles improve the total heat transfer due to a higher contribution of natural convection.

In the first phase of the present investigation, mini-bundle tests were made on an arrangement of two vertically aligned coated tubes with a pitch to diameter ratio of 4/3. The results for the upper tube can be seen in Fig. 7, while those for the lower tube agree well with Fig. 5. The general trend of the heat transfer coefficients seems to follow that for a single coated tube, while the effect of the saturation temperature is reduced at the upper tube.

The results of heat transfer experiments with four coated tubes in a rectangular arrangement can be found in Fig. 8. It is clearly evident that the heat transfer enhancement of the upper tubes decreases with increasing heat flux. Kulenovic et al. (2002) and Hsieh et al. (2002) investigated the effect of different arrangements of coated tubes on the boiling behaviour. Hsieh results showed a marginally higher effect of the bundle at 2-8 kW/m², while they also observed a decreasing bundle factor with increasing heat flux. This effect seems to be fairly independent of the saturation temperature, as shown in Fig. 9.

The tube bundle effect for smooth tubes can be calculated with Eq. (1) and Eq. (2), published in the VDI-Wärmeatlas based on the work of Bier et al. (1976), Slipcevic (1975) and Palen et al. (1981). The bundle effect η is defined as the average heat transfer coefficient of all tubes of the tube bundle, apportioned according to the respective surface area, divided by the heat transfer coefficient for a single tube.

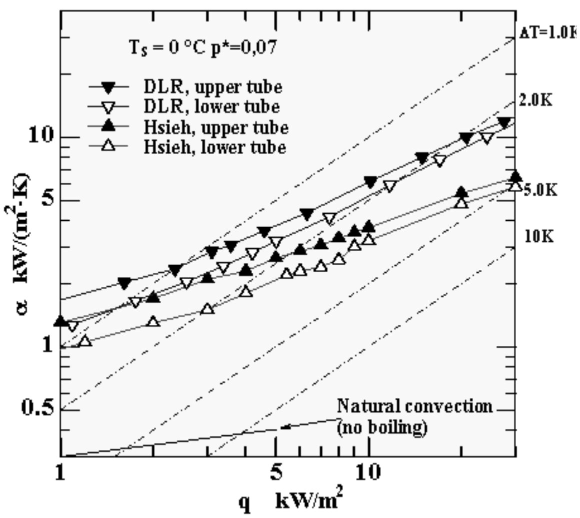


*Figure 8:Boiling heat transfer of two 2*2 tube bundle with different coating parameter*

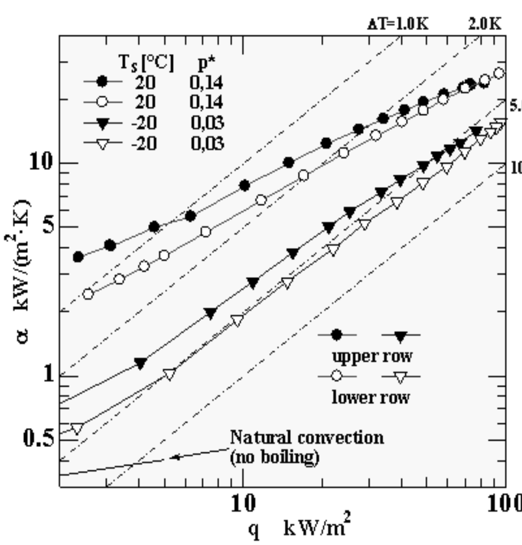


*Figure 9: Boiling heat transfer on the upper and lower row of a 2*2 tube bundle*

$$\eta = \frac{\overline{\alpha}}{\alpha_{ST}} \;;\; \overline{\alpha} = \frac{\sum A_i \cdot \alpha_i}{\sum A_i} \qquad (1)$$

The bundle effect dependency on the heat flux may be correlated for smooth tubes by Eq. (2), with φ =1. However, there is no appropriate correction factor for coated surfaces given in the literature until now.

$$\eta = 1 + \left(2 + \frac{\dot{q} \cdot \varphi}{1000 \;\; W/m^2}\right)^{-1} \qquad (2)$$

$$\varphi_{ST} = 1$$

It was found that Eq. (2) for smooth tubes can not be fitted with a constant value of φ to the results found in the present investigation. For example, in the case of two vertical in-line tubes, φ should be in the range of 0.75 to 1 for a heat flux of 4 kW/m², while it should be 0.06 to 0.12 at higher heat flux. The results of the heat transfer experiments with four tubes in a rectangular arrangement could be fitted with a factor φ of 0.2 to 0.5 at low heat fluxes, while there is a close correlation using φ= 0.24 at higher heat fluxes.

To provide a suitable correlation for bundles of coated tubes, Eq. (2) has to be modified.

In Table 1, the measured bundle factors for two tubes in vertical in-line arrangement are summarized. Obviously, the highest bundle factor is at high pressure. This effect is marginally caused by the enlarged turbulences due to the higher velocity at higher temperatures. For four tubes in a rectangular arrangement, the experiments produced the trends listed in Table 2. The improvement of four tubes seems to be most pronounced at low heat flux.

A closer look at the visible flow section indicates that that the enhancement is mainly due to the enlarged fluid velocity in the shell. Contrariwise, the decrease of the bundle factor for higher heat flux can be explained by a vapour film in the pitch of the upper tubes due to enhanced production of bubbles from the lower tubes. For industrial use of plasma coated tubes instead of smooth or finned tubes in heat exchangers, the fundamental information required is the extent to which a given evaporator is enhanced by the application of plasma coated tubes. Several experiments have been performed to determine the enhancement produced by adding only one coated tube into a smooth tube bundle consisting of four tubes. At each pressure, the oil temperature at the tube inlet was set to a value 10 K above the saturation temperature, while the incoming R-134a was kept 2 K subcooled.

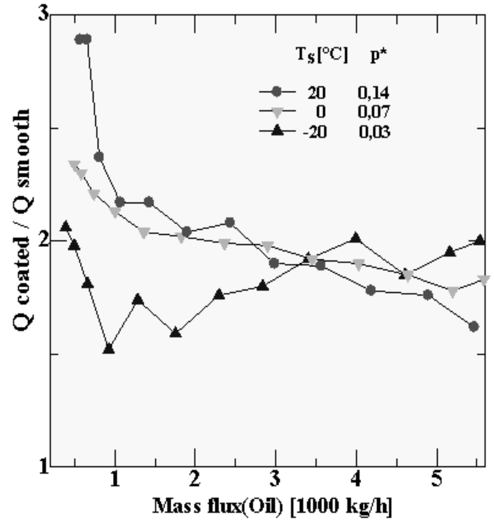
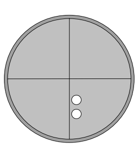


Figure 10: Enhancement of the transferred heat per coated tube

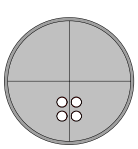
Fig. 10 shows the ratio of the enhancement factors of the modified tube bundle to those of the smooth tube bundle at three different saturation temperatures. The largest improvement is seen at low mass flux and higher pressure, as already observed for the single tube. The average improvement is close to 1.8 times the values for the smooth tube bundle.

Table 1: Tube bundle factors



p*	Two tubes in vertical in-line arrangement	
	low heat flux (4 kW/m²)	high heat flux (75 kW/m²)
0.14	1.2	1.15
0.072	1.16	1.09
0.033	1.17	1.06

Table 2: Tube bundle factors



p*	Four tubes in a rectangular arrangement	
	low heat flux (4 kW/m²)	high heat flux (75 kW/m²)
0.14	1.35	1.05
0.072	1.28	1.04
0.033	1.24	1.04

CONCLUSION

Nucleate pool boiling heat transfer of R134a on a tube bundle was analyzed for four plasma-spray coated tubes. The following results have been obtained

(1) Boiling heat transfer is enhanced over a wide range of heat fluxes and saturation pressures by a thin porous copper layer on the heating surface, with an enhancement of up to 4 times.

(2) The bundle experiments indicate that the well-known correlation for smooth tube bundles does not fit the experimental data with coated tubes.

(3) In general, there seems to be a consistent trend for the bundle factor to decrease to 1 for higher heat fluxes

(4) The replacement of smooth tubes by plasma coated tubes in a tube bundle leads, for identical entrance parameters, to an enhancement of 2-3 times.

NOMENCLATURE

A:	Surface	m²
P:	Pressure	kPa
q:	Heat flux	W/m^2
R_a:	Arithmetical mean surface roughness	µm
T:	Temperature	°C
α:	Heat transfer coefficient	$W/(m^2K)$
ε_0 :	open porosity	
η:	Bundle factor	
λ:	Thermal conductivity	W/(m K)
φ:	Surface factor	
C:	Critical	
S:	Saturation	
ST:	Smooth tube	

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