

# Pool Boiling Heat Transfer on structured Surfaces

**J Addy, M Olbricht, B Müller and A Luke**

Institute of Technical Thermodynamics, University of Kassel  
Kurt-Wolters-Straße 3, 34125 Kassel, Germany

E-mail: [ttk@uni-kassel.de](mailto:ttk@uni-kassel.de)

**Abstract:** The development in the process and energy sector shows the importance of efficient utilization of available resources to improve thermal devices. To achieve this goal, all thermal components have to be optimized continuously. Various applications of multi-phase heat and mass transfer have to be improved. Therefore, the heat transfer and the influence of surface roughness in nucleate boiling with the working fluid propane is experimentally investigated on structured mild steel tubes, because only few data are available in the literature. The mild steel tube is sandblasted to obtain different surface roughness. The measurements are carried out over wide ranges of heat flux and pressure. The experimental results are compared with correlations from literature and the effect of surface roughness on the heat transfer is discussed. It is shown that the heat transfer coefficient increases with increasing surface roughness, heat flux and reduced pressure at nucleate pool boiling.

## 1. Introduction

Enhancement of heating surfaces has been recognized as one efficient way to improve thermal devices. Several studies were made to investigate heat transfer augmentation on structured surfaces. Surface roughness has a significant impact on nucleate pool boiling heat transfer. More nucleation sites are activated and this leads to additional convective effects by up-streaming multiphase fluid. The influence of roughness is mainly described by form, size and distribution of the cavities within the topography of the heated surface. The cavity determines the superheat required for bubble nucleation, which implies that large cavity size demands lower superheat. The effect of roughness is also considered in semi-empirical correlations for the calculation of heat transfer in pool boiling. However, the information of the structure of the surface is often not sufficient so that different measurements are not comparable in literature.

The effect of surface roughness on heat transfer in pool boiling is already experimentally observed quite early by Jakob and Linke [1]. They show that the main augmentation is due to the increase of active nucleation sites. Stephan [2] studies experimentally the bubble formation entrapped in the cavities of heating surfaces and develops a simple relation to describe the influence of the roughness by a standardized roughness parameter. Researchers investigate mainly the influence of surface



roughness of copper tubes on the heat transfer in boiling refrigerants at ambient pressure. Nishikawa et al. [3] demonstrate that the influence of roughness is also a function of reduced pressure. Schömann et al. [4] confirm this by discussing the influence for the first time on steel tubes in boiling hydrocarbons and develop a newly defined roughness parameter. Luke [5] investigates a large variation of microstructure with different measurement procedures and transfer the methods of Stephan [2], and Schömann et al. [6] for the application of topographies. Luke and Kruck [7] and Luke and Bujok [8] study experimentally pool boiling of hydrocarbons on horizontal mild steel tubes with plain and enhanced surfaces. Müller et al. [9] investigate recently the microstructure of a drawn and a polished mild steel tube by a new optical measurement method.

In the present work, preparation and enhancement on mild steel tube is carried out with mechanical device to obtain fine, medium and rough sandblasted surface and the influence on the heat transfer are investigated. The surface roughness of mild steel tubes with different surface treatment is measured with contactless optical focus variation method. The heat transfer in pool boiling is investigated experimentally in a standard pool boiling apparatus using propane as working fluid over wide ranges of reduced pressure and heat flux from incipient to fully developed nucleate boiling. The experimental results are compared with different correlations from the literature considering heat transfer coefficient and surface roughness.

## **2. Surface Preparation and Results of the Roughness Measurement**

Before the mechanical treatment of the heating surface, the mild steel test tube is accurately polished with sandpaper of different grades starting from 400 until 2000. The surface is polished until a uniform surface structure is obtained. The blasting medium, the grain size, and hardness used in the treatment of the heating surface to attain fine, medium and rough sandblasted surfaces are shown in Table 1. The surface of mild steel is treated in a mechanical injector blast cabin. For a detailed description of the procedure see Luke [5]. The grain is blown by means of compressed air on the tube surface. The surface of the test tube is sandblasted by fine corundum grain. After sandblasting, the heat transfer measurements are carried out in a standard pool boiling apparatus. After the measurements, the procedure is repeated on the test tube for the medium and rough sandblasted surfaces with different grain sizes.

The microstructure of the mild steel test tube is investigated by a special contactless instrument for topography analysis according to the focus variation method. The instrument works by searching the best focus point by varying the lateral position. A detailed description of the optical based measurement system is given by Müller et al. [9]. The results of the various parameters depicting surface properties are summarized in Table 2 according to standard DIN EN ISO 4287 for two-dimensional parameters and acc. to DIN EN ISO 25178 for three-dimensional parameters. The two dimensional surface roughness profiles are characterized by unfiltered raw profile parameters such as the mean roughness  $P_a$ , root mean square  $P_q$ , maximum peak height  $P_p$ , maximum height of profile  $P_t$  and the mean distance between the highest peak and lowest valley in each sampling length is  $P_z$ . The mean unfiltered roughness parameter  $P_a$  is use in semi-empirical correlation to calculate the heat transfer coefficient in nucleate boiling according to VDI Heat Atlas [10]

Table 1: Parameter for the treatment of the mild steel heating surface by sandblasting

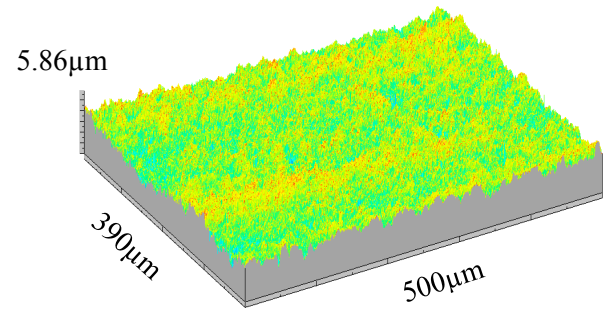
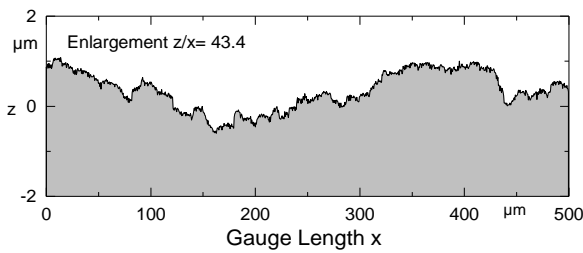
Processing	fine	medium	rough
Blasting medium	Corundum F320 $\text{Al}_2\text{O}_3 > 99\%$ $\text{SiO}_2 < 0.1\%$	Corundum F120 $\text{Al}_2\text{O}_3 > 99\%$ $\text{SiO}_2 < 0.1\%$	Corundum F 12 $\text{Al}_2\text{O}_3 > 99\%$ $\text{SiO}_2 < 0.1\%$
Grain size	16.5 - 49 $\mu\text{m}$	60 - 180 $\mu\text{m}$	1.20 bis 2.8 mm
Average grain diameter	$d = 29.2 \pm 1.5 \mu\text{m}$	-	-
Hardness	2100kg/mm <sup>2</sup> Knoop	2100kg/mm <sup>2</sup> Knoop	2100 kg/mm <sup>2</sup> knoop

Table 2: Roughness parameters of the fine, medium and rough sandblasted mild steel tube acc. to DIN EN ISO 4287 (10.98) with the gauge length  $x = 0.5\text{mm}$ , without cut-off ( $\lambda_c = \infty$ )

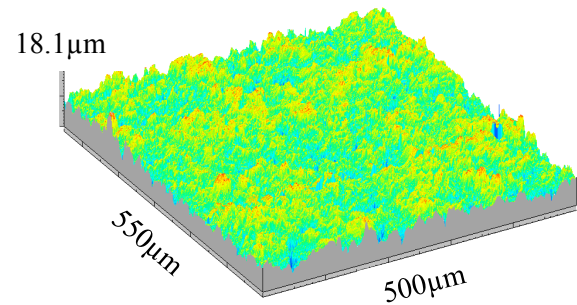
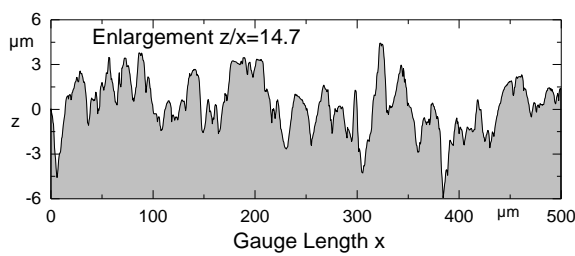
Diameter Treatment		$P_a$ [ $\mu\text{m}$ ]	$P_q$ [ $\mu\text{m}$ ]	$P_p$ [ $\mu\text{m}$ ]	$P_{pm}$ [ $\mu\text{m}$ ]	$P_t$ [ $\mu\text{m}$ ]	$P_z$ [ $\mu\text{m}$ ]	runs
D = 18.95 mm fine ( $p_L=1.5$ bar; $d_p=17-49 \mu\text{m}$ )	average max. min. $\sigma$	0.32 2.88 0.19 0.11	0.41 4.62 0.24 0.18	1.14 12.43 0.55 0.46	2.45 25.14 1.22 1.12	1.69 9.17 1.00 0.40	0.81 5.50 0.46 0.18	27912
D = 18.80 mm medium ( $p_L=3.0$ bar; $d_p=90-152 \mu\text{m}$ )	average max. min. $\sigma$	1.39 2.25 0.81 0.18	1.75 2.81 1.03 0.22	4.27 9.94 2.26 0.85	9.57 20.08 5.28 1.61	6.71 10.88 3.93 0.86	3.05 5.16 1.71 0.42	26197
D = 18.80 mm rough ( $p_L=3.5$ bar; $d_p=1400-2000 \mu\text{m}$ )	average max. min. $\sigma$	11.32 28.74 2.15 3.54	14.17 33.67 2.64 4.24	29.78 75.94 5.49 9.78	64.65 136.6 12.58 18.78	37.28 98.70 7.61 10.40	17.68 41.24 3.36 5.04	24640

The representation of characteristics profiles (left) and isometric topographies (right) for the fine (top), medium (middle) and rough (bottom) sandblasted surface are shown in Figure 1. A stochastic distribution of cavity sizes is observed on the heating surface. It can be recognized that both the topography and profile of the fine sandblasted surface are regular and characterized by waves with very small cavity sizes which may require high superheat for nucleation. The medium sandblasted surface profile varies equally and even distribution of cavity sizes as compared to fine sandblasted surface. The rough surface consists of coarse and larger cavity sizes in comparison to the medium and fine sandblasted surface. The topography of rough surface comprises peaks with different height and irregularities of profile which form the nucleation site and less superheat is demanded for nucleation as compared to medium and fine sandblasted surfaces.

fine sandblasted mild steel  $P_a = 0.32\mu\text{m}$



medium sandblasted mild steel tube  $P_a = 1.39\mu\text{m}$



rough sandblasted mild steel  $P_a = 11.32\mu\text{m}$

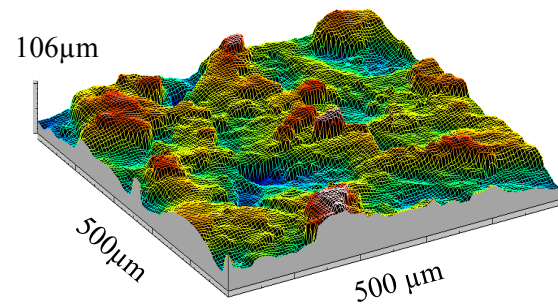
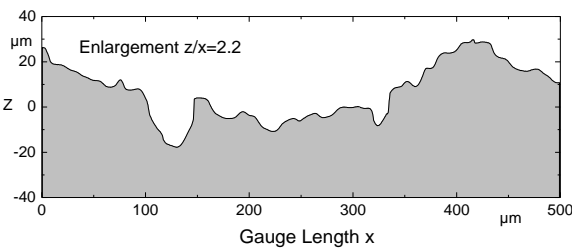


Figure 1: Representation of measured profiles (left) with their enlargement ( $z/x$ ) and isometric topographies (right) on a mild steel tube with fine (top), medium (middle) and rough (bottom) sandblasted surface.

### 3. Heat Transfer Measurements

Heat transfer measurements are conducted on the mild steel tube with modified surfaces as described in chapter 2 inside a standard pool boiling apparatus according to Gorenflo and Goetz [11] modified by Kaupmann et al. [12] and Luke and Kruck [7]. The test tube is placed horizontally in the evaporator connected to a natural circulation loop. The heat transfer experiments are carried out from high heat fluxes in fully developed nucleate boiling to convective boiling regimes to prevent hysteresis for different saturation pressures. The test tube itself is heated by an electrical DC-resistance heater. The wall superheat compared to the saturated boiling liquid is measured by thermocouples inside the tube wall and in the saturated liquid pool. The saturation pressure is measured by a pressure transducer and the saturation temperature is measured by two PT100 in the liquid and in the vapour phase. The saturation temperatures of propane are between  $-14^\circ\text{C}$  and  $60^\circ\text{C}$ .

The heat transfer coefficient  $\alpha$  is determined experimentally by measuring the heat input into the test tube and the temperature difference between the tube wall  $T_w$  considering heat transfer by conduction from thermocouples within the test tube to the surface and the saturation boiling liquid temperature  $T_s$  in the pool,

$$\alpha = \frac{\dot{Q}}{A\Delta T} = \frac{\dot{q}}{\Delta T} \quad (1)$$

where  $\dot{q}$  is the heat flux and  $\Delta T$  the temperature difference between the tube wall and the saturated liquid. The heat input into the tube is determined from the power input of the electric heater.

The heat transfer coefficient is reported as function of the heat flux in a double logarithmic graph for fine (top), medium (middle) and rough (bottom) sandblasted mild steel surfaces. The heat transfer coefficient augments strongly with increasing saturation pressure and heat flux. The reduced pressure is varied between 7% and 50% for fine sandblasted surface, and between 5% and 50% for medium and rough sandblasted surfaces of the critical pressure. The result shown in Figure 2, (top) depicts the characteristics behavior of pool boiling. The heat transfer coefficient  $\alpha$  is proportional to the heat flux  $\dot{q}$  with the slope  $n$  ( $p^*$ ) (eq. 3) as a function of reduced pressure in nucleate boiling. The curves obtained from the literature correspond quite well to the reduced pressures in figure 2.

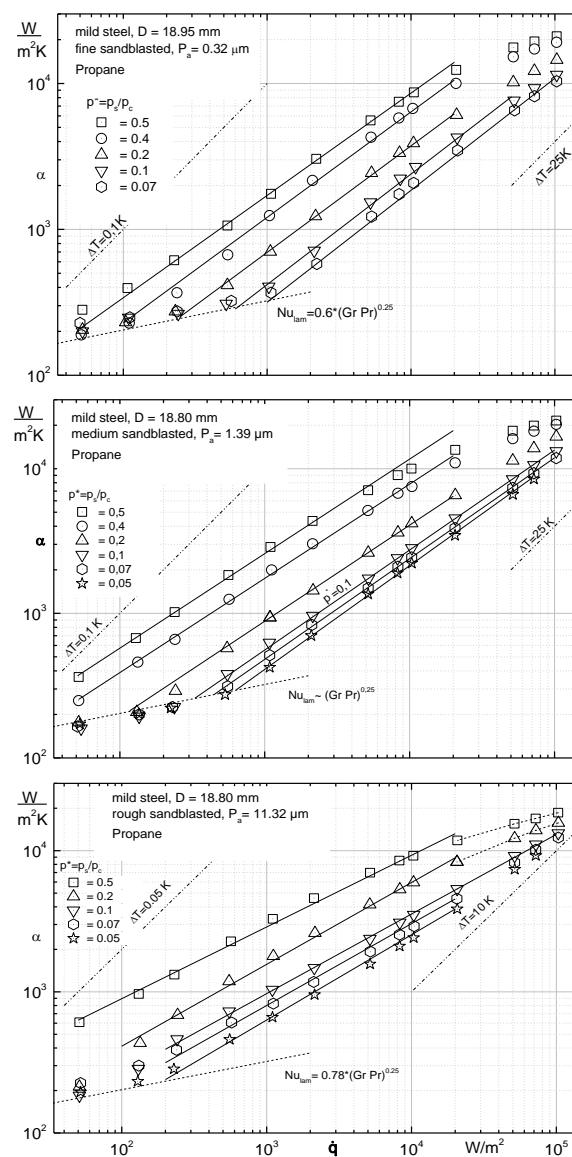


Figure 2: Heat transfer coefficient  $\alpha$  as a function of the heat flux  $\dot{q}$  at different reduced pressures with propane on fine, medium and rough sandblasted mild steel tube.

$$\alpha \sim q^{n(p^*)} \quad (2)$$

$$n(p^*) = 0.9 - 0.3p^{*0.3} \quad (3)$$

The heat transfer coefficient increases with increasing heat flux and reduced pressure until almost  $10^5$  W/m<sup>2</sup> where the slopes of the reduced pressures decreases at higher heat fluxes. The results demonstrate that the heat transfer coefficient is almost the same at higher pressures and heat fluxes and the slopes become steep. The heat transfer coefficient increases slightly at lower heat flux. For heat flux below 1000 W/m<sup>2</sup> without bubble formation, free convection correlations are used to determine the heat transfer coefficient, where the Nusselt number is a function of geometry of the heating surface, Grashof and Prandtl numbers for a laminar flow.

$$Nu \sim (GrPr)^{0.25} \quad (4)$$

The reduced pressure curves are clearly separated for fine, medium and rough sandblasted surface. The cavities on the medium sandblasted surface in figure 2, middle are much deeper than on fine surface. Large numbers of gases are entrapped in the cavities to elevate nucleation. The heat flux and superheat required for onset of nucleate boiling are 30% lower than for fine sandblasted surface. The heat transfer coefficient augments with increasing heat flux and reduced pressure. The number of active nucleation sites on the rough surface is more than on the fine and medium sandblasted surface for inception of nucleation. The nucleation sites on the rough sandblasted surface are stable and bubbles are activated in the large cavities on the rough surfaces. The rough sandblasted surface in figure 2, bottom with reduced pressure above  $p^*=0.1$  undergoes almost fully nucleate boiling without single phase natural convection. As observed for fine and medium sandblasted surfaces, it is observed that the reduced pressure lines decline at heat flux above 20kW/m<sup>2</sup>.

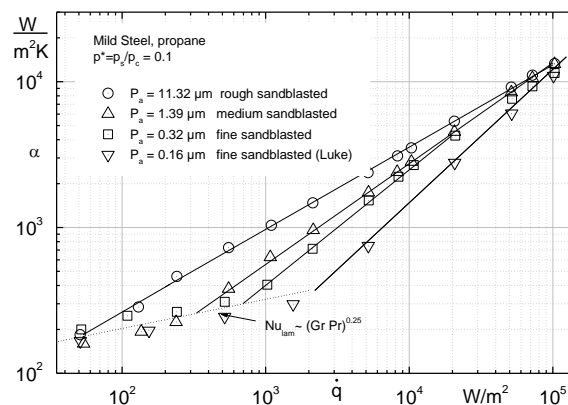


Figure 3: Comparison of the heat transfer on mild sandblasted tube with different surface roughness at a normalized pressure of  $p^*=0.1$

The heat transfer coefficient augments with increasing roughness for the pure fluid, see figure 3 for the comparison between fine, medium and rough sandblasted surface. The surface roughness of the rough surface in the form of the unfiltered mean roughness parameter is 8 and 35 higher than that of the medium and fine sandblasted surfaces respectively. More and smaller cavities are activated at smaller superheat. The heat transfer coefficient of the rough sandblasted surface at heat flux of 1 kW/m<sup>2</sup> is 2.5 times higher than the fine sandblasted surface and 1.6 times higher than the medium sandblasted surface. At heat fluxes above 20kW/m<sup>2</sup>, there are many unstable nucleation sites and the heat transfer

coefficient is independent of surface roughness. The influence of the slope and the reduced pressure on the heat transfer can be observed in figure 4 by comparing the different surface roughness at a constant heat flux of  $20\text{ kW/m}^2$ . As a consequence, the slope in eq. 3 agrees quite well for medium and fine sandblasted surfaces.

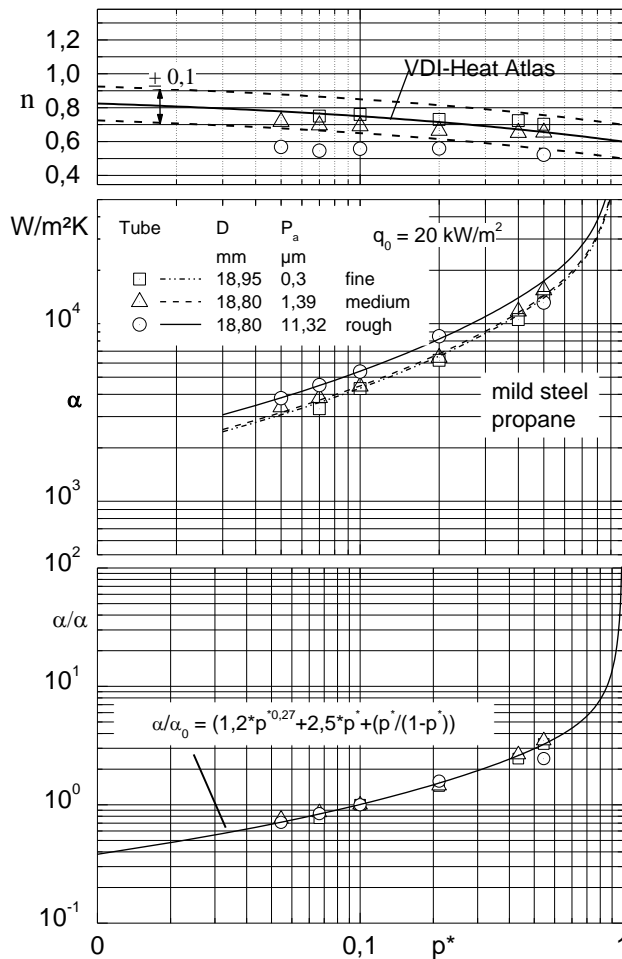


Figure 4: Pressure dependence of interpolated for  $q = 20\text{ kW/m}^2$  (middle) and of the slope of the interpretation lines  $n$  (top) for the investigations on the mild steel tube for propane in figure 2.

#### 4. Comparison with correlations in literature

Several correlations for pool boiling heat transfer in literature describing the influence of surface roughness on nucleate pool boiling are considered. The correlations are restricted to roughness range, pressure, heat flux and surface material. The correlations from Stephan [2], Nishikawa [3] and Luke [5] considering the influence of surface roughness on the heat transfer coefficient in nucleate boiling are used in combination with the correlation from VDI Heat Atlas [10]

$$\frac{\alpha}{\alpha_0} = F(p^*)(F_q)^{n(p^*)}(F_{WM})^{0.25}(F_{WR})^{0.133} \quad (5)$$

$F(p^*)$  is a function of the reduced pressure,  $F_q$  is heat flux,  $F_{WM}$  is thermal effusivity of heating material,  $F_{WR}$  is surface roughness,  $\alpha_0$  represents the thermophysical properties of the working fluid determined from experimental results or using the correlation from Stephan and Preusser [13] at the reference conditions:  $\dot{q}_0 = 20\text{ kW/m}^2$ ,  $p^* = 0.1$ ,  $R_{a0} = 0.4\mu\text{m}$ ,  $\lambda_0$ ,  $\rho_0$  and  $c_0$  represent the thermal

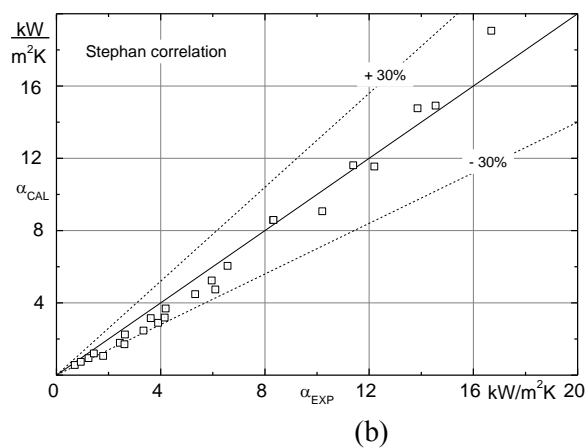
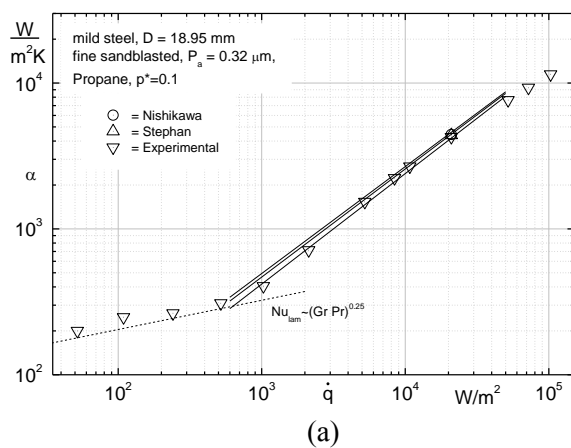
conductivity, density and specific heat capacity of polished copper surface respectively. The arithmetic mean surface roughness  $R_a$  in the correlation from eq. 5 is replaced with  $P_a$  since the investigated cross sectional area is very small and the deviation can be neglected. The correlation from eq. 5 used for fine sandblasted surface in figure 5a at heat flux of  $20 \frac{\text{kW}}{\text{m}^2}$  shows good agreement between the correlations of Stephan [2] and Nishikawa [3] with the experimental results. However the influence of surface roughness is underestimated for low roughness values. Furthermore, Nishikawa [3] observes that the surface roughness depends also on the reduced pressure. The correlation from Nishikawa [3] can be applied to a wider range of surface roughness as compared to Stephan [2], since the correlation of Stephan [2] was developed for atmospheric pressure. The results from Stephan [2] are in good agreement with the experimental results for sandblasted surfaces with a deviation of 30% (figure 5b). For rough surfaces, the correlation from Stephan [2] and Nishikawa [3] deviates from the experimental results considerably. Luke [5] modified the correlation from Stephan [2] for higher surface roughness. Luke [5] observed that the slope of the heat flux and the gradient of the surface roughness in eq. 5 for nucleate boiling heat transfer coefficient at higher surface roughness are interrelated. The gradient of the heat flux depends not only on reduced pressure, but also on surface roughness.

$$n(p^*) = 0.7222 - 0.2944p^{*0.37} + \frac{0.2777}{1+200\left(R_a/R_{a0}\right)^{10}} \quad (6)$$

The correlation from Luke [5] is compared to Stephan [2] and Nishikawa [3] for a rough sandblasted surface at a reduced pressure  $p^* = 0.5$  in figure 5c. The experimental results agree with high accuracy with the correlation from Luke [5].

Table 3: Relationship between the heat transfer coefficient and surface roughness correlations.

Author	Correlation	Eq.
Stephan [2]	$\alpha = R_a^{0.133}$	(7)
Nishikawa [3]	$\alpha = R_a^{0.2(1-p^*)}$	(8)
Luke [5]	$\alpha = R_a^{0.0375-0.0753\ln p^*}$	(9)





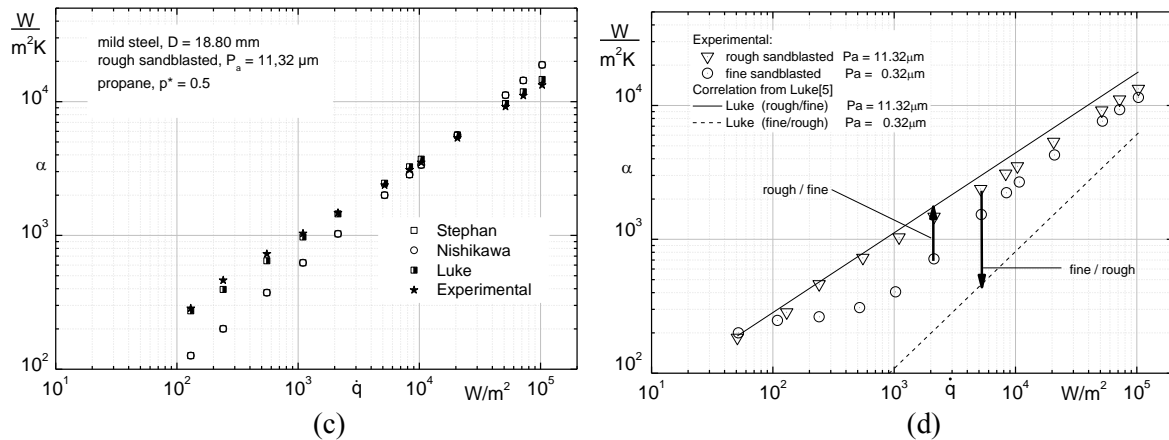


Figure 5: Comparison of the experimental heat transfer coefficient as a function of the heat flux with the correlation from Luke [5], Nishikawa [3] and Stephan [2] on the various process surfaces.

## 5. Conclusion

The heat transfer measurements are carried out in a standard pool boiling apparatus with propane as working fluid over wide ranges of reduced pressure and heat flux. The microstructure of the surface preparation and treatment on mild steel with different surface roughness are also investigated. The experiments are conducted on fine, medium and rough sandblasted surfaces. The rough sandblasted surface consists of irregular large cavities for inception of nucleation which requires low superheat as compared to medium and fine sandblasted surfaces. The heat transfer coefficient improves by 60% on the rough sandblasted surface as compared to the fine sandblasted surface for lower to intermediate heat flux. The heat transfer coefficient augments with increasing heat flux, saturation pressure and surface roughness. Furthermore, the correlation from Luke [5] is with high accuracy for rough surfaces, while the correlation from Stephan [2] agrees with the experimental results for fine and medium sandblasted surfaces with a deviation of 30%. Further experimental results are required to modify the correlation from Luke for low and medium surfaces at higher reduced pressures.

## Nomenclature

A	Area (m <sup>2</sup> )	d	Grain diameter (μm)
D	Tube diameter (m)	P	Surface roughness (μm)
q	Heat flux (W/m <sup>2</sup> )	T	Temperature (K)
$\alpha$	Heat transfer coefficient (W/m <sup>2</sup> K)	$\dot{Q}$	Heat flow (W)
$p^*$	Reduced pressure (-)	n	Slope (-)
$\lambda$	Thermal conductivity (W/m K)	$\rho$	Density (kg/m <sup>3</sup> )
c	Specific heat capacity (J/kg K)		

## Subscripts

a	Arithmetic	q	Quadratic
Exp	Experimental	Cal	Calculated
0	Reference	WM	Wall Material
WR	Wall Roughness		

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