

SUPERINTENDENCIA DE INDUSTRIA Y COMERCIO			
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DEP:	2020 DIRECCION DE NUEVAS CREACIONES	EVE:	378 FASE NACIONAL INCLUIDO CAPITULO I
TRA:	11 PCT-PATENTE DE INVENCION CAPITULOS I Y II	FOLIOS:	5
ACT:	519 PRESENTACION		

DIRECCIÓN DE NUEVAS CREACIONES

2020
Bogotá, D.C.,

Abogado(a)/Señor(a)
MAURICIO PATIÑO BONNET

Asunto: Radicación: 12-65762- -5
 Trámite: 11
 Evento: 378
 Actuación: 519
 Oficio: 11194
 Folios: 5

Patente de Invención	X			Patente de Modelo de Utilidad	
Vía Nacional					
Vía PCT (Fase Nacional)	X	Capítulo I	X	Capítulo II	
No. Solicitud Internacional	PCT/EP2010/065162				
Fecha de Presentación Internacional	11/10/2010				

Como resultado del Examen de Fondo realizado, con fundamento en el Artículo 45 de la Decisión 486 de la Comisión de la Comunidad Andina, se comunica:

1. Documentos estudiados

Descripción:	Rad. N° 12-065762-00000-0000	20/Abril/2012
Reivindicaciones:	Rad. N° 12-065762-00000-0000	20/Abril/2012
Prioridades:	DE 20 2009 045 882.4	21/Octubre/2009

2. Análisis de la Prioridad

Se acepta la reivindicación de Prioridad porque esta solicitud fue presentada dentro del plazo establecido (Art. 9 D 486) y su contenido técnico corresponde con el de la prioridad reivindicada.

3. Objeto de la invención

De acuerdo con lo establecido en el numeral 1.2.2.2 del Capítulo Primero del Título X de la Circular Única para efectos del examen de patentabilidad, se tendrá en cuenta la tasa pagada por el solicitante al momento de comenzar el examen para las reivindicaciones adicionales; esto es que cuando la solicitud contenga más de diez (10)

reivindicaciones y no se haya pagado la tasa complementaria, sólo se estudiarán las cubiertas por la tasa pagada.

Se aceptan para estudio todas las 8 reivindicaciones presentadas (Fls. 16 a 18 del Rad. N° 12-065762-00000-0000) porque las tasas pagadas cubren en su totalidad lo establecido en el numeral 1.2.2.2 del Capítulo Primero del Título X de la Circular Única.

Título de la solicitud: "Intercambiador de calor de fondo de pozo para bomba de calor geotérmica" (Fl. 1).

El problema planteado en esta solicitud consiste en la necesidad de aprovechar el calor geotérmico presente en los pozos de perforación.

Para resolver este problema técnico, la solicitud en estudio proporciona un intercambiador de calor con una tubería en capas de material polimérico y/o metálico con rugosidad en la superficie de contacto con el medio refrigerante que retira el calor.

El objeto de la presente Solicitud se relaciona con la Clasificación Internacional de Patentes (CIP) F24J 3/08.

4. Reivindicaciones relativas a un uso o a un segundo uso (Art 14 y 21 D 486)

El uso de las reivindicación 8 no es patentable, de acuerdo con el Art 14.

5. De la Solicitud de Patente

Reivindicaciones (Art 30 D 486, Art 22 PCT)

Las reivindicaciones 1, 2 y 3 no son claras porque las expresiones "*rugosidad media aritmética Ra de acuerdo con DIN EN ISO 4287*", "*promedio de altura de pico a valle Rz de acuerdo con DIN EN ISO 4287*" y "*máximo de altura de pico a valle Rz1maz de acuerdo con DIN EN ISO 4287*" son resultados a alcanzar, lo que no está permitido, no define al producto y/o método porque la invención no queda definida por el resultado a alcanzar, puesto que la reivindicación incluiría no sólo la solución propuesta por el solicitante, sino todas las alternativas presentes o futuras que lleguen a ese resultado. Se sugiere remplazarla por las características esenciales estructurales que contribuyen a la obtención de ese efecto.

La reivindicaciones 4 y 6 no son concisas porque las definiciones de composición moldeada termoplástica y fibras y/o cargas de refuerzo, son géneros funcionales, se sugiere restringir la solicitud a una razonable generalización del tipo de compuestos que han sido sintetizados ó probados, es decir, que se encuentran debidamente sustentados.

Las reivindicación 8 no es clara porque indica el uso que puede darse al producto reivindicado, el cual no es una característica técnica que defina a la invención. Se sugiere hacer la aclaración respectiva.

6. Determinación del Estado de la Técnica

El estado de la técnica se determinó con base en la fecha de presentación de la solicitud de prioridad invocada, es decir, el 21 de octubre de 2009.

Consultadas las fuentes de información con que se cuenta, se encontraron los siguientes documentos que anticipan el objeto de esta solicitud.

Item	Documento	Título	Fecha de Publicación
D1	ES 2110127	"Multi-layered plastic pipe"	05/Octubre/1994
D2	DE 20 2007016938	"Anlage zur geothermischen Energiegewinnung"	14/05/2009

El documento D1¹ divulga una tubería en capas de polímeros de poliamida y fluoro polímeros, entre otros (Pág. 3, líneas 15 a 49, Pág. 5, líneas 35 a 56).

El documento D2² divulga un sistema de intercambio de calor para recuperar calor presente en el suelo (Pág. 4, Párr. 38, Pág. 5, reivindicación 1, Fig. 1, Fig. 3).

7. Examen de Patentabilidad (Art 14 D486)

Novedad (Art 16 D486)

La reivindicación 7 consiste en *"El intercambiador de calor de fondo de pozo de acuerdo con cualquiera de las reivindicaciones 1 a 3, caracterizado..."* (Ver Fl. 17 del Rad. N° 12-065762-00000-0000).

Comparación de las características técnicas **esenciales**, con las del Estado de la Técnica:

Características esenciales	D2
Intercambiador de calor de fondo de pozo de acuerdo con cualquiera de las reivindicaciones 1 a 3, caracterizado porque la tubería del intercambiador de calor consiste metal.	Sistema de intercambio de calor con superficie rugosa en el interior de la tubería metálica (Pág. 4, Párr. 38, Pág. 5, reivindicación 1, Fig. 1, Fig. 3).
Donde la superficie interior tiene un recubrimiento rugoso.	Se tiene el interior rugoso lo cual mejora la transferencia (Pág. 5, reivindicación 1, Fig. 3).

De acuerdo con la tabla anterior, las características esenciales del intercambiador de la reivindicación 7 habían sido divulgadas previamente en el documento D1, por lo tanto, la materia reivindicada no es nueva.

La reivindicación 8 consiste en *"El uso de un intercambiador de calor de fondo de pozo de acuerdo con cualquiera de las reivindicaciones precedentes..."* (Ver Fl. 17 del Rad. N° 12-065762-00000-0000).

Comparación de las características técnicas **esenciales**, con las del Estado de la Técnica:

Características esenciales	D2
Intercambiador de calor de fondo de pozo de acuerdo con cualquiera de las reivindicaciones precedentes para recuperar energía geotérmica de un pozo de producción.	Sistema de intercambio de calor con superficie rugosa en el interior de la tubería metálica (Pág. 4, Párr. 38, Pág. 5, reivindicación 1, Fig. 1, Fig. 3).
Se usa un refrigerante vaporizable	Se emplea refrigerante vaporizable R723 (Pág. 3, Párr. 29 y Párr. 30).
El vapor refrigerante que ha ascendido esta comprimido y licuado en un compresor y el calor de condensación se retira como calor útil y	Se comprime pasando así a la fase líquida y se libera calor (Pág. 3, párr. 29 y Párr. 30).
El refrigerante líquido enfriado se suministra nuevamente al intercambiador de calor y se transporta en sentido descendente como película descendente	Se introduce de nuevo para su vaporización, descendiendo sobre la superficie del tubo (Pág. 3, Párr. 29, Pág. 4, Párr. 34 a Párr. 36).

¹http://worldwide.espacenet.com/publicationDetails/biblio?DB=worldwide.espacenet.com&II=0&ND=3&adjacent=true&locale=en_EP&FT=D&date=19980201&CC=ES&NR=2110127T3&KC=T3
²http://worldwide.espacenet.com/publicationDetails/biblio?DB=worldwide.espacenet.com&II=0&ND=3&adjacent=true&locale=en_EP&FT=D&date=20090409&CC=DE&NR=202007016938U1&KC=U1

De acuerdo con la tabla anterior, las características esenciales del método de la reivindicación 8 habían sido divulgadas previamente en el documento D2, por lo tanto, la materia reivindicada no es nueva.

Nivel inventivo (Art 18 D486)

La reivindicación 4 consiste en “*El intercambiador de calor de fondo de pozo de acuerdo con cualquiera de las reivindicaciones precedentes, caracterizado...*” (Ver Fl. 16 del Rad. Nº 12-065762-00000-0000).

Comparación de las características técnicas **esenciales**, con las del Estado de la Técnica:

Características esenciales	D1	D2
Intercambiador de calor de fondo de pozo de acuerdo con cualquiera de las reivindicaciones precedentes, caracterizado porque	No se menciona	Sistema de intercambio de calor con superficie rugosa ^{3,4} en el interior de la tubería metálica (Pág. 4, Párr. 38, Pág. 5, reivindicación 1, Fig. 1, Fig. 3).
la tubería del intercambiador de calor consiste en una o más capas donde cada una consiste en una composición moldeada termoplástica	Tubería multicapa de poliamidas, fluoro polímeros, entre otros, que responden a dilatación térmica (Pág. 3, líneas 15 a 49, Pág. 5, líneas 35 a 56).	No se menciona

Los documentos D1 y D2 se consideran el estado de la técnica más cercano a la invención definida en la reivindicación 4, porque divulgan tuberías en capas de polímero y sistemas de intercambio de calor con tuberías en capa.

La diferencia entre la invención, definida en la reivindicación 4 y la tubería del documento D1 consiste en que D1 no menciona la rugosidad.

La diferencia entre la invención, definida en la reivindicación 4 y el intercambiador del documento D2 consiste en que en D2 no se menciona las capas de polímero en la tubería.

El efecto que logra el incluir la rugosidad en la tubería en el sistema de intercambio de calor es que permite un intercambio de calor del pozo con el refrigerante de forma más eficiente.

Por lo tanto, el problema técnico objetivo que pretende resolver esta invención se puede formular así “¿cómo modificar la tubería de D1 para que cuando haga parte de un sistema de intercambio de calor sea más eficiente?”.

Sin embargo, la rugosidad como parámetro de importancia en la vaporización, ya está divulgado en el documento D2 que se refiere a un sistema de intercambio de calor con superficie rugosa en el interior de la tubería metálica (Pág. 4, Párr. 38, Pág. 5, reivindicación 1, Fig. 1, Fig. 3).

³Gogonin II, The dependence of boiling heat transfer on the properties and geometric parameters of heat.transfer wall. High temperature. Vol. 44 (6). 2004. Pág.915, Tabla. 1, Pág. 917, Pág. 918, Tabla 2.
⁴Jabardo et al, Roughness and surface material effects on nucleate boiling heat transfer from cylindrical surfaces to refrigerants R-134a and R-123. Experimental thermal and fluid science. Vol. 33. 2009. Pág. 582. Tabla. 2 Págs. 586 y 590.

En consecuencia, una persona normalmente versada en la materia incluiría la rugosidad de D2 en la tubería de la anterioridad D1, esperando con certeza lograr el intercambiador de calor, como la de la reivindicación 4 de la solicitud, lo cual es considerado obvio y, por lo tanto, sin altura inventiva.

Puesto que las reivindicaciones dependientes 5 y 6 no mencionan características adicionales que hagan inventiva la solicitud, se considera que tales reivindicaciones tampoco tienen nivel inventivo, ya que D1 divulga en la tubería de capas, de poliamida y fluoro polímero, la presencia de fibras de carbono al 15% en la tubería, siendo implícito para la persona versada en la materia la importancia en la rugosidad de la superficie de contacto de la tubería con el líquido en la transferencia de calor, por lo que es cuestión de ensayar diversas rugosidades en la tubería para encontrar el que más favorezca a la transferencia^{3,4} (Pág. 5, líneas 41 y 42).

8. Conclusión

Los requisitos de Patentabilidad de la presente Solicitud están afectados así:

Item	Documento	Reivindicaciones afectadas	Requisito que afecta
D1	ES 2110127	4 a 6	Nivel inventivo
D2	DE 20 2007016938	7 y 8	Novedad/ Nivel inventivo
		4 a 6	Nivel inventivo

En cumplimiento del artículo 45 de la Decisión 486 de la Comisión de la Comunidad Andina, se le indica que debe dar respuesta dentro del término de sesenta (60) días contados a partir de la fecha de notificación de la presente comunicación. En caso de no dar respuesta al presente requerimiento, o si a pesar de la respuesta subsistieran los impedimentos para la concesión, se denegará la patente.

Se invita al solicitante se sirva indicar, si así lo considera, su renuncia al término faltante de sesenta (60) días para dar respuesta a este requerimiento y presentarla por escrito.

Finalmente, se le recuerda al solicitante que si como respuesta a este requerimiento llegara a modificar el capítulo reivindicatorio y éste contenga más de diez (10) reivindicaciones, no pagará la tasa de modificación voluntaria pero sí la correspondiente al pago por reivindicación adicional.

Notifíquese el presente oficio conforme a lo dispuesto en el numeral 5.2, literal e), del capítulo quinto del título primero de la Circular Única No. 10 de 2001.



JOSÉ LUIS SALAZAR LÓPEZ
Director de Nuevas Creaciones (c)

El anterior requerimiento fue notificado por fijación en lista, de fecha 2013-07-02

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HEAT AND MASS TRANSFER AND PHYSICAL GASDYNAMICS

The Dependence of Boiling Heat Transfer on the Properties and Geometric Parameters of Heat-Transfer Wall

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Abstract—Analysis of the available data reveals that the parameters of boiling heat transfer depend significantly on the thermophysical properties of the heat-transfer wall and its geometric characteristics (roughness and thickness of the wall). However, it is still difficult to correctly estimate in full the effect of roughness and thickness of the heat-transfer wall. It is possibly because of this that no universal criterial relations exist at present which would enable one to describe the vast array of experimental data on boiling heat transfer. A particular problem is treated in this paper and generalization is given of experimental data on boiling heat transfer of Freons and nitrogen to thick-walled pipes of different thermophysical characteristics and roughness.

INTRODUCTION

Various aspects of boiling heat transfer are treated in most detail in the monographs [1–8] whose authors treat ambiguously the effect of the thermophysical characteristics of the cooled wall on the mechanism and intensity of boiling heat transfer. Grigor'ev *et al.* [2] demonstrated that the boiling heat transfer of cryogenic liquids depends significantly on the thermophysical characteristics of the wall and its thickness, all other things being equal. However, Kutepov *et al.* [6] believe that the same value of heat-transfer coefficient is observed under conditions of boiling of ordinary liquids on walls of copper, brass, German silver, and stainless steel.

It is the objective of this study to determine the effect of the thermophysical properties of the heat-transfer wall on the intensity of heat transfer under conditions of ordinary liquids. Analysis of experimental data of different authors was based on the modified criterial equation of Labuntsov [9, 10] suggested for the description of boiling heat transfer under conditions of free convection.

GENERALIZATION OF EXPERIMENTAL DATA

The mechanism of heat transfer from the heat-transfer wall to boiling liquid and the model of bubble

growth most thoroughly validated by Labuntsov in [9] are given in Fig. 1. The bubble consists of two parts, namely, a curvilinear top part, which is a truncated sphere of radius R , and a bottom part defined by the conical surface of microlayer. The bubble grows at the expense of evaporation of liquid from the surface of microlayer whose thickness is time-independent.

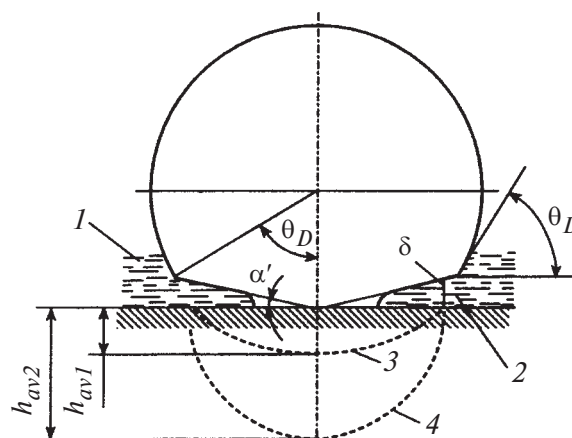


Fig. 1. The scheme of delivery of heat to a growing vapor bubble and the front of propagation of temperature disturbance in a solid: (1) superheated layer of liquid, (2) microlayer at the bubble base, (3) isotherm in a material of low heat-conducting properties, (4) isotherm in a material of high heat-conducting properties.

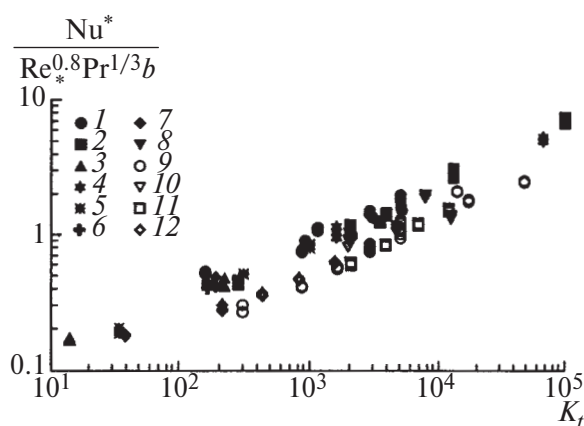


Fig. 2. Heat transfer under conditions of Freon boiling on thick-walled pipes of copper and stainless steel. Copper: (1) R12 [18, 20, 23]; (2) R22 [14, 20, 23]; (3) R11 [23]; (4) propane [14]; (5) R114 [19]; (6) R113 [24], (7) R123 [23], (8) R134 [23]. Stainless steel: (9) R12 [11, 17, 21], (10) R113 [21], (11) R22 [11], (12) R142 [11].

In Fig. 1, θ_D is some average value of dynamic wetting angle during the period of bubble growth; α' is the angle between the generating conical surface of microlayer and the heating surface; and h_{av1} and h_{av2} denote the cooling depth for low-heat-conducting and high-heat-conducting materials of the wall, respectively.

It follows from numerous experimental studies (for example, [11–17]), where the measurements were performed strictly under conditions of free convection in the experimental volume of liquid, that the exponent of the number Re_* must be taken to be 0.8. Then, the criterial relation of Labuntsov may be represented in the form

$$\frac{Nu^*}{Re_*^{0.8} Pr^{1/3} b} = f(K_t). \quad (1)$$

Here, $Nu^* = \frac{\alpha \delta}{\lambda}$, where

$$\delta = \sqrt{\frac{\sigma}{g(\rho' - \rho'')}}, \quad Re_* = \frac{q \delta}{r \rho'' v}, \quad K_t = \frac{(r \rho'')^2 \delta}{C_p T_s \rho' \sigma},$$

$$\text{and } b = \left[1 + 10 \left(\frac{\rho''}{\rho' - \rho''} \right)^{2/3} \right].$$

Note that the results of experiments under conditions of boiling of different liquids in a wide range of variation of pressures and heat fluxes are described fairly well in the coordinates of (1), provided these

experiments are performed using thick-walled heaters of one and the same material of the same roughness.

Figure 2 illustrates the processing of the results of experiments in boiling of various Freons on thick-walled copper pipes [14, 18–23] and on thick-walled pipes of stainless steel [11, 17, 22]. Table 1 gives the range of variation of basic parameters of the quantities being measured in performing these experiments.

Table 1 refers only to the experiments with the published complete description of the experimental procedure and complete characteristics of heat-transfer surface, which make it possible to estimate the value of δ_w/h_{av} .

In order to eliminate the effect of hysteresis corresponding to transition from free convection to boiling with increasing and decreasing heat flux, the experimental results were processed without the points corresponding to this range of variation of heat fluxes.

Analysis of the data in Fig. 2 leads one to conclude that the material of heat-transfer surface affects the intensity of boiling heat transfer. It will be emphasized that the boiling of R12 Freon on a copper surface was investigated in [8, 20–23], and that on a stainless steel surface – in [11, 17, 22]. At $K_t = \text{idem}$, the heat transfer on copper pipes turns out to be more intense than that in the case of cooling of stainless steel pipes by a factor of approximately 1.8.

The processing of experimental results in the coordinates of (1) makes it possible to determine the exponent of the thermal similarity criterion K_t . Relation (1) may be written as

$$Nu^* = C Re_*^{0.8} Pr^{1/3} K_t^{0.4} \left[1 + 10 \left(\frac{\rho''}{\rho' - \rho''} \right)^{2/3} \right]. \quad (2)$$

The fundamental disadvantage of relation (2) is the total absence of any characteristics of heat-transfer surface in similarity criteria.

The Effect of Wall Parameters

Analysis of the mechanism of boiling heat transfer, performed in [2, 5], enables one to supplement the Labuntsov relation with dimensionless parameters which characterize the heat-transfer wall. In this case, the Nusselt number will be a function of the following criteria:

$$Nu^* = f \left(Re_*; Pr; K_t; b; \bar{R}_z; \frac{\delta_w}{h_{av}}; \sqrt{\frac{\lambda C_p}{\lambda_w C_w \rho_w}} \right). \quad (3)$$

Table 1. Heat transfer under conditions of boiling of Freons on thick-walled pipes

Author, year of publication	Substance	Temperature range	Material	Diameter (width), mm	Wall thickness, δ_W , mm	R_z , μm	Range, q , W/m^2	δ_W/h_{av}
Danilova G.N., 1965 [11]	R12	−17–20°C	stainless steel	12.5	0.2	—	$10^3\text{--}1.5\times 10^4$	>10
	R22	−10–20°C	>>	12.5	0.2	—	$10^3\text{--}1.5\times 10^4$	>10
	R142	−10–20°C	>>	12.5	0.2	—	$10^3\text{--}1.5\times 10^4$	>10
Danilova G.N. and Bel'skii V.K., 1965 [12]	R12	22°C	steel10	10	0.5	0.35–3.5	$10^4\text{--}5\times 10^4$	>10
	R113	46°C	copper	10	0.5	0.35–3.5	$10^4\text{--}5\times 10^4$	~1.0
			steel10 copper					>10 ~1.0
Gorenflo, 1968 [13]	R11	31–58°C	copper	12.0	—	2.4	$10^3\text{--}10^5$	—
	R113	−8–62°C	>>	12.0	—	2.4	$10^3\text{--}10^5$	—
	R22	−10–61°C	>>	12.0	—	2.4	$10^3\text{--}10^5$	—
Gorenflo, 1991 [14]	propane	−21–50.5°C	copper	8.0	1.0	2.8	$10^3\text{--}10^5$	>10
	R22	−10–61.5°C	>>	8.0	1.0	2.8	$10^3\text{--}10^5$	>10
Bel'skii V.K., 1970 [17]	R12	−25–46°C	stainless steel	17.7	0.3	0.95	$0.7\times 10^3\text{--}10^4$	>10
Dyundin V.A., 1969 [18]	R12	−30–20°C	copper	16.0	3.0	3.4	$5\times 10^3\text{--}10^5$	>10
Henrici-Hesse, 1971 [19]	R114	−20–30°C	copper	30	4.0	2.0	$5\times 10^3\text{--}5\times 10^4$	>10
Heimbach, 1972 [20]	R12	−27–11°C	copper	16	1.0	2.4	$10^4\text{--}3\times 10^4$	>10
	R22	−38–0.3°C	copper	16	1.0	2.4	$10^4\text{--}3\times 10^4$	>10
Ratiani G.V. and Avaliani D.I., 1965 [21]	R113	47–140°C	stainless steel	9.25	0.5	—	$5\times 10^3\text{--}10^5$	>10
	R12	18–67°C		9.25	0.5	—	$5\times 10^3\text{--}10^5$	>10
Schroth, 1968 [22]	R12	−13–45°C	St. 35	25	2.5	9.0	$10^3\text{--}2.5\times 10^4$	>10
	R11	6–28°C	St. 35	25	2.5	9.0	$10^3\text{--}2.5\times 10^4$	>10
Webb-Pais, 1992 [23]	R12	4.44–26.7°C	copper	17.5	4.0	—	$10^4\text{--}8\times 10^4$	>10
	R11	>>	>>	>>	>>	—	>>	>10
	R22	>>	>>	>>	>>	—	>>	>10
	R123	>>	>>	>>	>>	—	>>	>10
	R124	>>	>>	>>	>>	—	>>	>10
Ayub-Bergles, 1990 [24]	R113	47	copper	25.4	7.95	—	$5\times 10^3\text{--}10^5$	>10
Danilova G.N., 1968 [25]	R12	−42–40°C	stainless steel	1.3	0.1	—	$10^3\text{--}4\times 10^4$	~1.0
	R142	10–20°C	>>	1.3	0.1	—	$10^3\text{--}4\times 10^4$	~1.0

Cooling depth

We will consider in more detail the effect of each one of the additional criteria in relation (3). Note that one of the criteria δ_W/h_{av} in (3) may hardly be calcu-

lated at present. The cooling depth h_{av} , which depends on the dynamic wetting angle θ_D , is defined in [2] as

$$h_{av} = \frac{2\pi\sqrt{5}}{9} R_0 \sin \theta_D \sqrt{a_W n \tau_p}. \quad (4)$$

It is demonstrated in [2] that the dynamic wetting angle θ_D is one of the least investigated parameters of growth of vapor bubbles on a solid surface. No relations are available for its calculation. It is recommended in [2] to determine the number of effective bubbling sites by the formula

$$n = C_n^2 \left[\frac{r\rho''\Delta T}{\sigma T_s \left(1 + 2\frac{m}{A}\right)} \right]^2. \quad (5)$$

$$\text{Here, } A = \frac{R_0}{\sqrt{\tau_p}} \text{ and } m = \frac{\lambda' \sqrt{\frac{2}{3}} \pi a_w}{\lambda_w \alpha' \sin \theta_D}.$$

It is difficult to calculate the number of bubbling sites in the absence of experimental data. In expression (5), the proportionality factor C_n^2 is not a constant but may vary several-fold depending on the combination of the metal of the heat-transfer wall and the liquid boiling on this wall [2].

The quantity τ_p appearing in Eq. (4) may be calculated by the formula

$$\tau_p = r\rho'' R_0^2 / \beta \lambda' \Delta T. \quad (6)$$

The proportionality factor β in the Labuntsov relation (6) may be determined only after the processing of experimental data.

One can use the experimental results of [25] and, with some assumptions, estimate the values of h_{av} in the boiling of Freons. The experiments referred to in [25] are characterized by a wide variation of the saturation temperature (from -40 C to $+40$ °C) at a low value of specific heat flux. The experiments involved high-speed filming, with the results of processing given in tabular form.

In addition to q in W/m^2 and $\Delta T = t_w - t''$, average statistical values of the bubble radius are given, as well as the time of its growth at a given pressure. The experimentally determined time of bubble growth and its radius enable one to calculate the proportionality factor in the Labuntsov relation (6),

$$\beta = \frac{r\rho'' R_0^2}{\tau_p \lambda' \Delta T}. \quad (7)$$

According to the data of Danilova [25], the average value of β in the boiling of Freons is 11.3. The generalization of numerous experimental data by the bubble

separation diameter, published in [26], enables one to determine the bubble radius for any pressure. The approximation relation given in [26] has the form

$$\bar{D} = 0.25 \sqrt{1 + 10^5 K}, \quad (8)$$

where $K = \left(\frac{Ja}{Pr}\right)^2 / Ka$.

If we assume that the dynamic wetting angle θ_D in the boiling of Freons and nitrogen is the same, we can use relations (5) and (7) and calculate approximately the value of h_{av} by formula (4). This assumption is possible because Freons wet the surfaces of metals as adequately as nitrogen does it. In performing calculations for determining the cooling depth h_{av} , the values of θ_D were taken to be independent of saturation temperature and the same for all Freons. The angle α' between the generating conical surface of microlayer and the heating surface (see Fig. 1) was estimated according to [27], where the formula is given for calculating the thickness of film beneath the growing bubble. The value of proportionality factor C_n^2 in formula (5) was taken to be 2.4×10^{-9} .

In view of the assumptions made, the calculation of cooling depth may be regarded as a parameter determined by the order of magnitude. Therefore, it was only on condition of $\delta_w/h_{av} > 10$ that the heat-transfer wall was regarded as "thick" (see Table 1). The points in Fig. 2 and in subsequent figures correspond to this condition.

Figure 3 gives the results of processing the experimental data in Table 1 on heat transfer under conditions of boiling of Freons on thick-walled pipes of different materials. They are compared with the data of similar experiments in nitrogen boiling published in the monograph of Grigor'ev *et al.* [2]. Comparison is made in the coordinates

$$\frac{Nu^*}{Re^{0.8} Pr^{1/3} b K_t^{0.4}} = f\left(\sqrt{\frac{\lambda C_p}{\lambda_w C_w \rho_w}}\right). \quad (9)$$

One can see in Fig. 3 that the heat transfer in boiling of Freons, similar to nitrogen boiling, is a function

of complex criterion $\sqrt{\frac{\lambda C_p}{\lambda_w C_w \rho_w}}$.

Comparison of experimental results in coordinates (9) implies that all of the experiments, the data of which are given in Fig. 3, were performed with thick-walled heaters of the same relative roughness. In real-

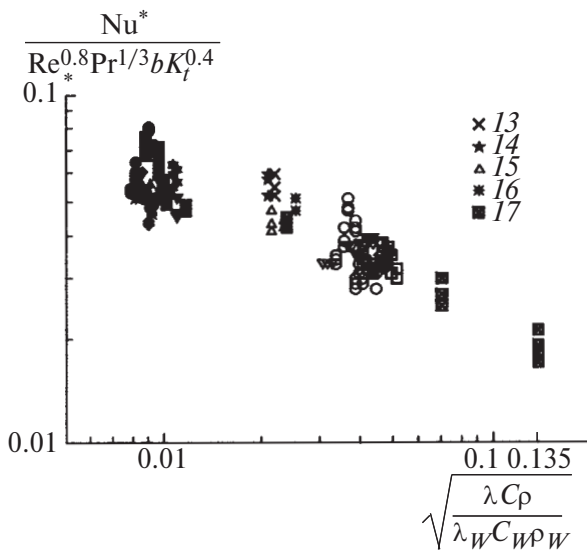


Fig. 3. Heat transfer in boiling of Freons and nitrogen as a function of thermophysical properties of heat-transfer surface: (1–12) see Fig. 2. Steel 10: (13) R12 [12], (14) R113 [12]. Steel 35: (15) R12 [22], (16) R11 [22], (17) nitrogen (copper, brass, bronze, stainless steel) [2].

ity, the latter condition was not strictly observed; this resulted in additional scatter of data in comparing the experimental results even in the case of boiling of Freons.

Note that the experiments in nitrogen boiling were performed at atmospheric pressure only, and the experiments in boiling of Freons were performed in a wide range of variation of pressure.

The experimental results confirm that the effect of the material of heat-transfer wall on the intensity of heat transfer is a general regularity in boiling of different liquids.

Wall roughness

It is emphasized in sections dealing with the effect of roughness of heat-transfer surface on boiling heat transfer in the monographs [2, 3, 5] that the surface roughness is one of the major factors defining the intensity of heat transfer in nucleate boiling of liquids. It was experimentally found that an increase in roughness causes the boiling curve to shift to the region of low temperature heads [12, 28]. Almost all researchers observe that a limit exists where a further increase in roughness fails to result in enhancement of heat transfer. The heat transfer depends significantly both on the distribution of recesses in size and on the shape of recesses and, consequently, on the method of treatment of heat-transfer wall. An example may be pro-

vided by the experimental results of [29], where the boiling heat transfer was investigated on surfaces of the same roughness but produced either by way of mechanical treatment of the wall or by etching the surface in hydrochloric acid solution. Measurements reveal that the mean-square roughness is not a universal characteristic of surface. Vachon *et al.* [29] obtained different values of temperature head for different technologies of production of roughness in the case of the same value of mean-square roughness and preassigned heat flux. Therefore, we consider only studies in which the surface roughness was produced mechanically. The surface roughness in accordance with GOST (State Standard) 2729-73 is characterized by the height of irregularities R_z , which is the only quantitative characteristic of surface roughness given in papers on boiling heat transfer.

Systematic investigations of heat transfer in boiling of R12 and R113 refrigerants on copper and steel pipes of different roughness are reported in [12]. In this study, the roughness is characterized by the height of irregularities R_z which was varied in the range of $0.3 \leq R_z \leq 58 \mu\text{m}$. Table 2 from [12] gives the parameter R_z for each surface and the procedure for producing a surface of preassigned roughness. It is shown in Table 1 that only steel pipes may be regarded as thick-walled in this study. Experiments with Freon R113 were performed at atmospheric pressure, and those with Freon R12 – at $6 \times 10^5 \text{ Pa}$. Jung *et al.* [30] varied the roughness of different copper regions within $1.56 \leq R_z \leq 11.7 \mu\text{m}$. Unfortunately, the wall thickness of experimental sections was not given, and the results of these experiments cannot be used in processing.

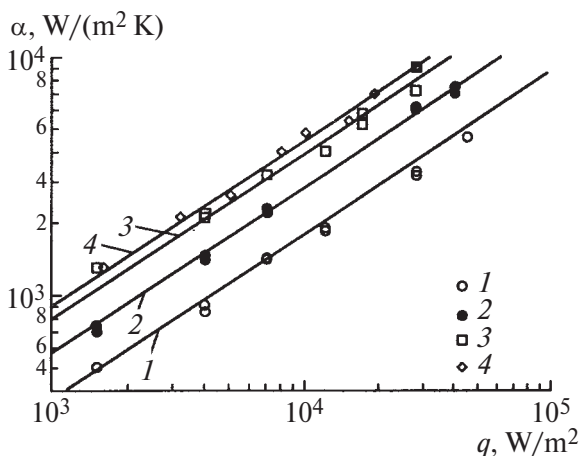
Figure 4 of [12] gives variations of coefficients of heat-transfer in boiling of Freon R12 on steel pipes of different roughness.

The value of heat flux corresponding to the onset of boiling decreases with increasing roughness. In the opinion of the authors, the basic results of the experiments are as follows: with the same value of q in W/m^2 , the number of effective bubbling sites increases, the wall-liquid temperature head decreases, and the heat-transfer coefficient increases.

It is assumed in the model of Fig. 1 that the bubble growth occurs owing to the evaporation of liquid from the surface of superheated microlayer whose thickness is time-independent. The latter assumption implies that the microlayer is renewed owing to the

Table 2. Heat transfer in boiling of Freons on surfaces of different roughness [12]

Characteristics of surface	Designation of pipe	Dimensions, mm		Length		Material	Method of treatment	Class of surface finish	Height of irregularities, μm	Instrument employed for assessment
		Outside diameter	Wall thickness	overall	working					
Rough treatment (high roughness)	A_S	10	0.5	100	90	steel 10	cutter in a lathe	$\nabla 3$	51.5	MIS-11
	G_S	10	1	118	108	steel	shot blasting	$\nabla 3$	53.5	MIS-11
	E_S	10	0.5	100	90	steel 10	abrasive grain charging	$\nabla 5$	20	profilograph made by Kalibr factory
	G_m^h	7	0.5	121.8	111.8	red copper	shot blasting	$\nabla 3$	58	MIS-11
	E_M	10	0.5	100	90	ditto	abrasive grain charging	$\nabla 5$	11.4	MIS-11
	$\frac{B_S}{B_{S1}}$	10	0.5	100	90	steel 10	trimming in a lathe	$\nabla 7$	6.3	visually by sample
Smooth surface (medium class of surface finish)	B_M	10	0.5	100	90	copper	coarse-grained abrasive cloth	$\nabla 7_a$ $\nabla 6_b$	5.3 8.04	MIS-11 MIS-11
	D_m^h	7	0.5	121.8	111.8	ditto	rolling without special treatment	$\nabla 8_c$	1.93	MIS-11
	V_S	10	0.5	100	90	steel 10	polishing	$\nabla 11_b$	0.3	MIS-5
High class of surface finish after grinding and polishing	V_M	10	0.5	100	90	copper	ditto	$\nabla 10_c$	0.45	MIS-5

**Fig. 4.** Coefficients of heat transfer in boiling of Freon-12 on steel pipes of different roughness [12]: (1) $R_z = 0.3 \mu\text{m}$, (2) 5.3, (3) 20, (4) 53.5.

liquid flowing under the growing bubble. If we assume that the flow of film under the bubble is laminar, the inner scale of such flow is provided by the viscous-gravitational constant of liquid

$$l_v = \left(\frac{\nu^2}{g(1 - \rho''/\rho')} \right)^{1/3} \quad [31, 32]. \quad \text{Then, the ratio}$$

$R_z/l_v = \bar{R}_z$ will provide the natural scale of relative roughness.

Figure 5 illustrates the processing in the coordinates

$$\frac{\text{Nu}^*}{\text{Re}^{0.8} \text{Pr}^{1/3} b K_t^{0.4}} = f(\bar{R}_z) \quad (10)$$

of the experimental data of [12] under conditions of boiling of Freons R12 and R113 on surfaces made of steel of different roughness.

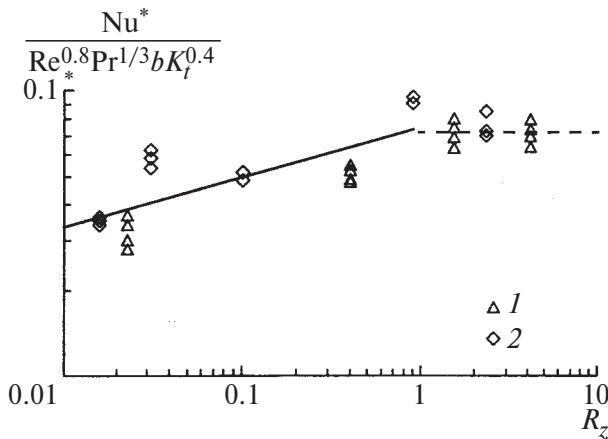


Fig. 5. The processing of experimental data of [12] in boiling of Freons R12 and R113 on steel pipes of different roughness: (1) R12, (2) R113.

Comparison of the experimental results in coordinates (10) implies that the complex criterion is

$$\sqrt{\frac{\lambda C \rho}{\lambda_w C_w \rho_w}} = \text{idem.}$$

One must bear in mind that, beginning with some limiting value of $\bar{R}_z$, the boiling heat transfer becomes independent of dimensionless criterion of roughness. For example, in the case of nitrogen boiling in [2], this limit was registered at $\bar{R}_z = 0.64$, and in the case of boiling of R113 – at $\bar{R}_z = 0.9$ [12]. It follows from the results of experiments given in Fig. 5 that, at $\bar{R}_z < 0.9$, the heat transfer is enhanced with increasing roughness and

$$\text{Nu}^* \sim (\bar{R}_z)^{0.2}. \quad (11)$$

At $\bar{R}_z > 0.9$, the heat transfer may be taken to be independent of this parameter.

In view of (11), the data given in Table 1, where the roughness of heat-transfer surface is indicated, may be represented as

$$\frac{\text{Nu}^*}{\text{Re}_*^{0.8} \text{Pr}^{1/3} b K_t^{0.4} \bar{R}_z^{0.2}} \equiv N = f\left(\sqrt{\frac{\lambda C \rho}{\lambda_w C_w \rho_w}}\right). \quad (12)$$

Figure 6 illustrates the processing of experimental data in coordinates (12). The results of experiments in heat transfer under conditions of boiling of different Freons on thick-walled pipes at different pressures are adequately generalized by a unified relation. Also given in this figure are all of the experimental results given

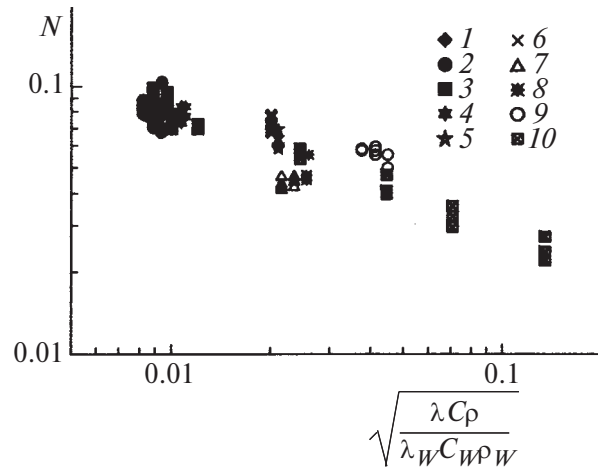


Fig. 6. Generalization of experimental data in boiling of Freons and nitrogen on heat-transfer surfaces of different materials and different roughness. Copper: (1) R114 [19], (2) R12 [18, 20], (3) R22 [20, 14], (4) propane [14]. Steel 10: (5) R12 [12], (6) R113 [12]. Steel 35: (7) R12 [22], (8) R11 [22]. Stainless steel: (9) R12 [17], (10) nitrogen (copper, brass, bronze, nickel, stainless steel) [2].

in Fig. 5 and obtained under conditions of boiling on pipes whose roughness was varied within $0.3 \leq \bar{R}_z \leq 53.3 \mu\text{m}$. Figure 6 further gives data of [2] obtained under conditions of nitrogen boiling on thick-walled cylinders made of materials exhibiting different thermophysical properties; in coordinates (12), these data agreed adequately with experimental data obtained under conditions of boiling of Freons.

In processing the experimental data, the thermophysical properties of Freons were determined by reference book [33], the properties of nitrogen – by [34], and the physical properties of metals – by [35, 36].

CONCLUSIONS

The empirical relation describing the results of generalization of experimental data, has the form

$$\text{Nu}^* = 0.01 \text{Re}_*^{0.8} \text{Pr}^{1/3} b K_t^{0.4} \bar{R}_z^{0.2} \left(\frac{\lambda C \rho}{\lambda_w C_w \rho_w}\right)^{-0.2}. \quad (13)$$

Relation (13) may be recommended for the calculation of heat transfer in boiling of cryogenic liquids and Freons on cooled walls on condition that $\delta_w/h_{av} > 10$. The range of validity of Eq. (13) under conditions of boiling of other liquids may be extended only after comparison with the results of respective experiments.

The data given in this paper make it possible to hold that the thermophysical properties of heat-transfer wall have a significant effect on boiling heat transfer for both cryogenic liquids and Freons.

Notation

α , coefficient of boiling heat transfer, in $W/(m^2 \text{ deg})$; A , modulus of vapor bubble growth in relation (5), in $m/s^{1/2}$; α_W , thermal diffusivity of metal, in m^2/s ; C_p and C_W , heat capacity of liquid and metal of heat-transfer surface, in $J/(kg \text{ deg})$, respectively; C_n^2 , proportionality factor in relation (5); D , cylinder diameter, in m ; D_0 and R_0 , separation diameter and radius of bubble, in m , respectively; g , acceleration of gravity, in m^2/s ; h_{av} , cooling depth calculated by formula (4); m , parameter in relation (5), in $m/s^{1/2}$; n , density of bubbling sites according to (5), in $1/m^2$; ρ' , ρ'' , and ρ_W , density of liquid, vapor, and metal of heat-transfer surface, in kg/m^3 , respectively; R_z , height of irregularities of heat-transfer surface, in μm ; r , latent heat of vaporization, in J/kg ; q , specific heat flux, in W/m^2 ; λ and λ_W , thermal conductivity of liquid and metal, in $W/(m \text{ deg})$, respectively; t_s in $^{\circ}C$ and T_s in K , saturation temperature; δ_W , thickness of heat-transfer wall, in m ; σ , surface tension, in N/m ; ν , kinematic viscosity, in m^2/s .

Subscripts and superscripts: ' and '', for liquid and vapor, respectively; W , characteristic of heat-transfer surface; *, criteria constructed by the capillary constant; p , at constant pressure; 0, size at the instant of separation; av , averaged value; s , at saturation temperature.

Dimensionless parameters: $Nu^* = \frac{\alpha \delta}{\lambda}$, Nusselt

number; $Re_* = \frac{q \delta}{r \rho'' \nu}$, Reynolds number; $Pr = \nu/a$,

Prandtl number; $K_t = \frac{(r \rho'')^2 \delta}{C_p T_s \rho' \sigma}$, thermal similarity

criterion; $b = \left[1 + 10 \left(\frac{\rho''}{\rho' - \rho''} \right)^{2/3} \right]$, dimensionless

complex; $\bar{R}_z = \frac{R_z}{l_v}$, dimensionless surface rough-

ness; $\sqrt{\frac{\lambda C_p}{\lambda_W C_W \rho_W}}$, dimensionless complex; δ_W/h_{av} ,

dimensionless value of wall thickness; β , proportion-

ality factor in (7); $\bar{D} = D_0/\delta$, dimensionless diame-

ter of separation bubble; $Ja = \frac{C_p \Delta T \rho'}{r \rho''}$, Jacob

number; $Ka = \sqrt{\frac{\sigma^3}{\nu^4 \rho^3 g}}$, Kapitza number; K , dimen-

sionless parameter in (8); N , dimensionless parameter

in (12).

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Roughness and surface material effects on nucleate boiling heat transfer from cylindrical surfaces to refrigerants R-134a and R-123

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ABSTRACT

This paper presents results of an experimental investigation carried out to determine the effects of the surface roughness of different materials on nucleate boiling heat transfer of refrigerants R-134a and R-123. Experiments have been performed over cylindrical surfaces of copper, brass and stainless steel. Surfaces have been treated by different methods in order to obtain an average roughness, R_a , varying from $0.03\ \mu\text{m}$ to $10.5\ \mu\text{m}$. Boiling curves at different reduced pressures have been raised as part of the investigation. The obtained results have shown significant effects of the surface material, with brass being the best performing and stainless steel the worst. Polished surfaces seem to present slightly better performance than the sand paper roughened. Boiling on very rough surfaces presents a peculiar behavior characterized by good thermal performance at low heat fluxes, the performance deteriorating at high heat fluxes with respect to smoother surfaces.

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1. Introduction

The effect of the heating surface condition on nucleate boiling heat transfer has called the attention of the scientific community as early as the thirties, when the first pioneering studies of the phenomena were being carried out. The need to understand the effect of the surface condition was apparent in the early models of nucleate boiling and boiling inception. Experimental studies have also been performed since the early sixties aiming at understanding and evaluating the surface roughness effects. Despite the large number of authors investigating such a topic, to find the relation between active cavities and the surface micro-structure is one of the key unsolved issues in the prediction of nucleate boiling heat transfer coefficient as pointed out by Dhir [1] and Yagov [2].

In his comprehensive experimental boiling study involving polished surfaces (mirror finish) and different mesh sizes scaled (sand paper treated) surfaces, Berenson [3] suggested that the heat transfer coefficient could be incremented fivefold by roughening the heating surface. He claimed that surfaces with higher roughness present higher nucleate boiling heat transfer coefficient due to higher active cavity density. Sauer et al. [4] came to a similar conclusion in their experimental results with refrigerants and polished and scaled (sand paper treated) surfaces. They claimed that increments of up to 20% in the heat transfer coefficient could be

obtained by roughening a polished surface. Roy Chowdhury and Winterton [5] carried out experiments with water and methanol boiling on copper and aluminium surfaces. They arrived at similar conclusions as the previous studies adding that comparisons should be performed only among surfaces submitted to the same treatment since the procedure could affect significantly the heat transfer coefficient. Benjamin and Balakrishnan [6], based on previous results from the literature and on their own data for water, CCl_4 , n -hexane, and acetone, developed an empirical correlation in order to predict the number of active sites. In their correlation, the nucleation site density was written as a function of the surface roughness, the thermophysical properties of the heating surface and the liquid, wall superheating, and saturation pressure. They found that the nucleation site density reaches a minimum with the increment of the surface roughness. Kang [7] carried out experiments with water at atmospheric pressure on surfaces of different orientation. As in the previous studies, Kang concluded that the heat transfer coefficient increases with the surface roughness, the increment being more significant for vertical surfaces as compared to the horizontal ones. Boiling experiments have been carried out by Gorenflo et al. [8] on horizontal copper cylindrical surfaces, finishing being provided by scaling, and shot pinning procedures. Several refrigerants have been tested including such hydrocarbons as propane and butane. As expected, their results have shown that the heat transfer coefficient increases with the surface roughness. In addition they claim that higher differences on surface superheat at the onset of nucleate boiling are related to differences in the

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Nomenclature

C_{sf}	surface/fluid coefficient [21]
D	tube diameter (m)
f_p	surface material coefficient [23]
h	heat transfer coefficient ($\text{W/m}^2 \text{K}$)
M	molecular mass (kg/mol)
m	exponent of the heat flux
n	exponent of p_r , Cooper correlation, Eq. (4)
P	abbreviation of “polished” surfaces
p	pressure (kPa)
p_c	critical pressure (kPa)
p_r	reduced pressure ($p_r = p/p_c$)
q	heat flux (W/m^2)
Ra	arithmetical mean deviation of the profile, ISO 4287/1:1984 (μm)

R_p	maximum peak height of the profile, DIN 4762/1:1960 (μm)
SP	abbreviation of “sand paper” roughened surfaces
SPI	abbreviation of “shot pinned” surfaces
T	temperature (K)
y	distance to the average line of the roughness peaks and valleys (μm)

Greek symbols

ΔT	wall superheating, ($T_w - T_{\text{sat}}$), (K)
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Subscripts

sat	saturation
w	tube wall

maximum cavities size of the surfaces. On the other hand, lesser differences in the minimum cavities size of the tested surfaces correspondingly determine lesser differences in the surface superheating in the high heat flux range, and, as a result, closer heat transfer coefficients for surfaces of different roughness.

An extensive review on the parameters affecting nucleate boiling heat transfer was recently published by Pioro et al. [9]. In their work, they highlighted the fact that surface roughness may affect the heat transfer coefficient only in case that the change in the surface roughness is within the range of the diameter of the active bubble centers. Consequently, the creation of larger cavities filled with liquid would not change the heat transfer coefficient as in case of grooves which according to the authors are ineffective vapor traps unless they are very poorly wetted. Luke [10] showed that the standard two-dimensional characterization of the surface is not effective and a complete understanding is needed of the link between the surface micro-structure and the evaporating process. This might be accomplished by considering the distribution of cavities using a three-dimensional approach to the surface characterization. Luke combined the stylus technique with the near field acoustic microscopy to characterize the three-dimensional micro-structure of copper tubes of 8 mm and 25 mm diameter with different roughness obtained by shot pinning and rolling the surface. The results were used to determine the density of potential active sites.

Hahne and Barthau [11] performed nucleate boiling heat transfer tests on horizontal tubes for R-134a and R-114. They obtained experimental results on gold-plated copper tube ($D = 15 \text{ mm}$, $Ra = 0.30 \mu\text{m}$), emery ground copper tubes ($D = 8$ and 15 mm , $Ra = 0.52 \mu\text{m}$ and $0.40 \mu\text{m}$, respectively), and stainless steel sand-blasted tube ($D = 15 \text{ mm}$, $Ra = 0.18 \mu\text{m}$). Lower heat transfer coefficients on the upper region of the tube were observed with the difference becoming negligible at high reduced pressures. The variation in the wall temperature along the tube circumference became steeper as the tube thermal conductivity is diminished. Such behavior have been previously pointed out by Ribatski et al. [12] based on their results for R-11 on copper and stainless steel tubes for heat fluxes up to 40 kW/m^2 . At higher heat fluxes, Ribatski et al. [12] pointed out an opposite trend with higher heat transfer coefficients on the upper region of the tube. Hahne and Barthau [11] and Ribatski et al. [12] indicated lower heat transfer coefficients for stainless tubes. Curiously, according to Hahne and Barthau [11] at the reduced pressure of 0.5, gold-plated and sand-blasted copper tubes provided higher heat transfer coefficients than the emery ground copper tube, while at the reduced pressure of 0.1, their performance were similar.

Though not directly related with the objectives and procedures of the present investigation, it must be recognized that to better

understand the boiling mechanism a simultaneous research of surfaces with artificial sites might be needed. Several nucleate boiling studies with surfaces containing artificial cavities have been recently performed [13–17]. An interesting study was performed by Chaptun et al. [13] on the effects of the cavities arrangement (inline and equilateral triangle) for four cavities spacing (1–4 mm) on the nucleate boiling characteristics of water at atmospheric pressure on a heated silicon surface. According to their results, an inline pattern generates a higher bubble detachment frequency while a triangular pattern generates larger bubble detachment diameters. At low heat fluxes, it was found that the bubble detachment diameter increases while the bubble detachment frequency decreases with cavity spacing. At low heat flux, they suggested that the inline pattern with the optimum cavity size provides a better performance. Das et al. [17] investigated the effect of active site spacing (10, 7.5 and 5 mm) on the heat transfer coefficient for water at atmospheric pressure. Artificial cavities were drilled according to a square arrangement on a copper plate previously polished with progressively fine grades of emery. A heat transfer coefficient enhancement up to 100% was obtained for a site spacing of 10 mm when compared to the smooth tube. Further heat transfer enhancements were obtained when decreasing the active site spacing down to 7.5 mm and 5 mm.

This paper reports results from an investigation of two fluorocarbon refrigerants, R-134a and R-123, boiling on horizontal cylindrical surfaces of copper, brass and stainless steel submitted to different finishing treatment. The objective of the study has been to investigate the combined effects of material and surface roughness on nucleate boiling heat transfer, a summary of the obtained results will be presented herein.

2. Experimental set up and procedures

The experimental set up comprises the refrigerant and cooling circuits, as shown in Fig. 1. The charge of refrigerant is basically contained in the boiler in which the liquid is kept at a reasonable level above the test surface (tube) so that the column head does not affect significantly the equilibrium saturation temperature. The cooling circuit is intended to control the equilibrium pressure in the boiler by condensing the refrigerant boiled in the heating surface. The condensing effect is obtained by a 60% solution of ethylene glycol/water that operates as intermediate fluid between the condenser and the cooling system not shown in Fig. 1. The ethylene glycol/water solution is cooled by either a refrigeration circuit or water from a cooling tower, depending on the operating pressure. This solution is intended to operate in the range between -26°C and 90°C .

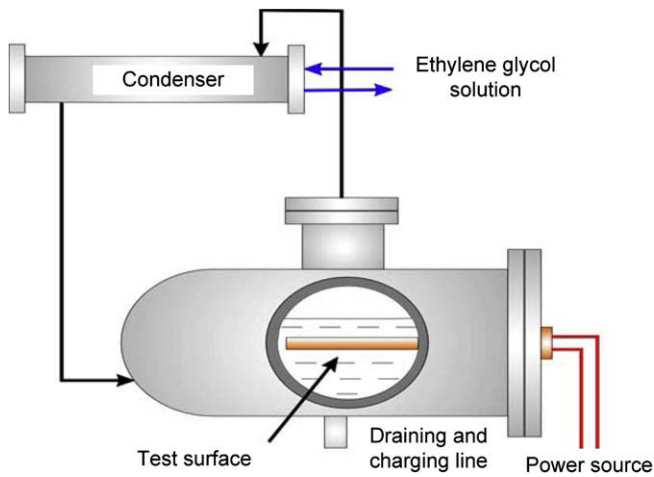


Fig. 1. A schematic diagram of the experimental set up with the main components and equipment.

The boiler is a 40 l carbon steel container with two lateral circular windows for visualization. It contains the boiling surface in addition to a 1500W/220V electrical heater, installed at the bottom, and two sheathed type *T* thermocouples. The boiler is also fitted with openings for connections to a pressure transducer, a safety valve, and vapor and liquid return copper lines, as shown in Fig. 1. The sheathed thermocouples are installed in such a way to measure and monitor the temperature of the liquid pool and the vapor in equilibrium with it. Before logging data, the readings of these thermocouples used to be checked and compared with the saturation temperature corresponding to the reading from the boiler pressure transducer. The allowable reading differences between these temperatures should be within the range of temperature uncertainty. It must be noted that these differences were well within the uncertainty range for all the logged data.

The test (boiling) surface is placed in the middle of the boiler so that the boiling mechanism can easily be visualized through the glass windows. It is made up of a 19.0 mm diameter and 3.1 mm thick tube, a longitudinal cut way view of it is shown in Fig. 2. The test tube is supported by a brass piece which is thread attached to the flanged cover of the boiler. The boiling surface is heated by a 12.6 mm diameter and 210 mm long cartridge electrical heater. The electrical power to the boiling surface is controlled by a manually operated voltage converter and measured by a power transducer. Surface temperature is measured through eight 30 AWG type *T* thermocouples installed in grooves carved by an electro erosion process in locations indicated in Fig. 2. A tool has been developed to introduce the thermocouples in the designated

place of the grooves and guarantee that the junction touches the tube wall, supposedly at the closest section of the groove from the surface. Thermocouples are kept in place by a thermal conductive epoxy resin. Before the resin curing in an oven, a test used to be performed to check if all thermocouple junctions touched the tube wall. This test consisted in checking the electrical conductance between the thermocouple wires and the tube wall.

Electrical signals from the transducers are processed by a data acquisition system which includes two 12 bit A/D converter boards with 16 channels each, and three connection panels. Two of these panels are dedicated to thermocouple connections.

The boiling surface used to be treated prior to the beginning of the tests. Three procedures have been used in treating the surface: (1) scaling (SP) with sand paper applied to the surface rotated by a regular lathe machine run at 1200 rpm, the mesh size varying in the range from 220 to 1200; (2) polishing (P) the surface previously scaled with sand paper; and (3) "shot pinning" (SPI) the surface with glass micro spheres of controlled size and sand previously sieved. After the surface treatment, the boiling surface used to be thoroughly cleaned with a solvent and the roughness measured at 10 randomly selected regions before attaching it to the boiler. After testing the boiling surface, 10 randomly selected regions were again taken for roughness measurement so that conditions of the surface before and after the tests could be compared. The roughness was measured in terms of the CLA arithmetic average, *Ra*. The treatment suggested above allowed experiments to be run in the range of surface roughness, *Ra*, between 0.03 μm and 10.5 μm .

The internal surface of the boiler used to be cleaned and kept under a vacuum of <2 kPa during a period of 12 h before the introduction of the test refrigerant. Tests were conducted under saturated conditions of the refrigerant. This condition was continuously monitored and adjusted as needed. As mentioned before, the datum point would only be logged if the readings of the sheathed thermocouples were close enough to each other and to the saturation temperature inside the boiler obtained from the pressure transducer reading. For analysis purposes, the saturation temperature of the pool was determined as the average of the readings of the sheathed thermocouples. Tests were conducted by gradually increasing the heat flux up to its predicted maximum. Once the maximum was attained, the heat flux was gradually reduced down to zero. Only downward heat flux data were considered for analysis purposes. Several procedures were tried to check for possible effects on the results. Two of such procedures consisted in keeping the boiling surface active for some time before logging data and starting directly from the maximum heat flux.

The heat transfer coefficient has been evaluated by the Newton's cooling law:

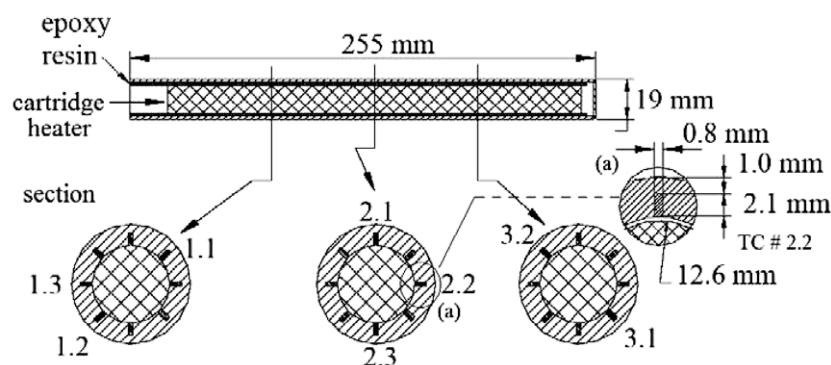


Fig. 2. Longitudinal and transversal cut views of the test section showing the location of the surface thermocouples.

$$h = \frac{q}{\Delta T} \quad (1)$$

where ΔT stands for the surface superheating, that is, $\Delta T = T_w - T_{\text{sat}}$.

The saturation temperature, T_{sat} , has been measured using the procedure previously described. In measuring the surface temperature care was exercised in evaluating the thermal resistance of the cylindrical wall between the thermocouple location and the actual boiling surface. A numerical analysis involving the test tube wall in a region encompassing the thermocouple groove and the surface has been performed in order to investigate the effects of both the position of the thermocouple junction and the groove over the calculated surface temperature. The uncertainty of the surface temperature (see Table 1) includes the result of this investigation, Stelute [18]. In addition, axially located thermocouples helped in evaluating axial heat conduction. It has been determined that in the location corresponding to section 2 of the test tube, Fig. 2,

Table 1
Uncertainty of measured and calculated parameters.

Parameter	Uncertainty
Minimum heat flux, $q = 0.60 \text{ kW/m}^2$	$\pm 1.8\%$
Maximum heat flux, $q = 120 \text{ kW/m}^2$	$\pm 0.3\%$
Heat transfer area	$\pm 0.3\%$
Heating surface temperature	$\pm 0.2 \text{ K}$
Saturation temperature (bath)	$\pm 0.2 \text{ K}$
Superheating of the heating surface	$\pm 0.3 \text{ K}$
Heat transfer coefficient, minimum uncertainty	$\pm 1.3\%$
Heat transfer coefficient, maximum uncertainty	$\pm 20.3\%$

Table 2
Surface average roughness, R_a , for each finishing procedure (μm).

Finishing procedure	Copper	Brass	Stainless steel
Polished (P)	0.07	0.08	0.03
Sand paper (SP)	0.16/0.47/0.50	0.16/0.90	0.04/0.07/0.16/0.45
Shot pinning (SPI)	2.5/3.3/4.6/10.5	1.2/1.4/1.8/3.0/3.5	0.90/1.1/1.45/2.0/2.5/3.2

the axial heat flux was negligibly small. The temperature considered for analysis purposes was the one from the thermocouple #2.2, located midway between those at top and bottom at section 2 (Fig. 2). The temperature indicated by this thermocouple is equivalent to the average of the readings of the three section 2 thermocouples, as discussed in detail by Ribatski et al. [12].

The maximum heat flux was limited to a maximum of 60 kW/m^2 during the experiments with stainless steel since the heating surface used to be intermittently covered with vapor patches at heat fluxes higher than this limit. Thus, in order to prevent reaching critical heat flux conditions, the heat flux was limited to this relatively low value compared to the ones used for the other two materials, respectively, 80 kW/m^2 and 120 kW/m^2 , for the brass and copper surfaces.

Instruments were calibrated and the uncertainty of measured parameters evaluated according to the procedure suggested by Abernethy and Thompson [19] with results summarized in Table 1. Additional information regarding the experimental set up and procedures can be found in Stelute [18] and Ribatski [20].

3. Characteristics of the heating surfaces

The roughness characteristics of the heating surfaces have been obtained through the three processes previously described. The surface roughness resulting from these processes is indicated in Table 2. The final aspect of the copper surfaces finished both with sand paper and the shot pinned is illustrated in the micro-photographs of Fig. 3. The effect of the finishing procedure is very clear in these pictures. Grooves from the scaling process, oriented in a preferential direction, are clearly noted in Fig. 3a. The shot pinning

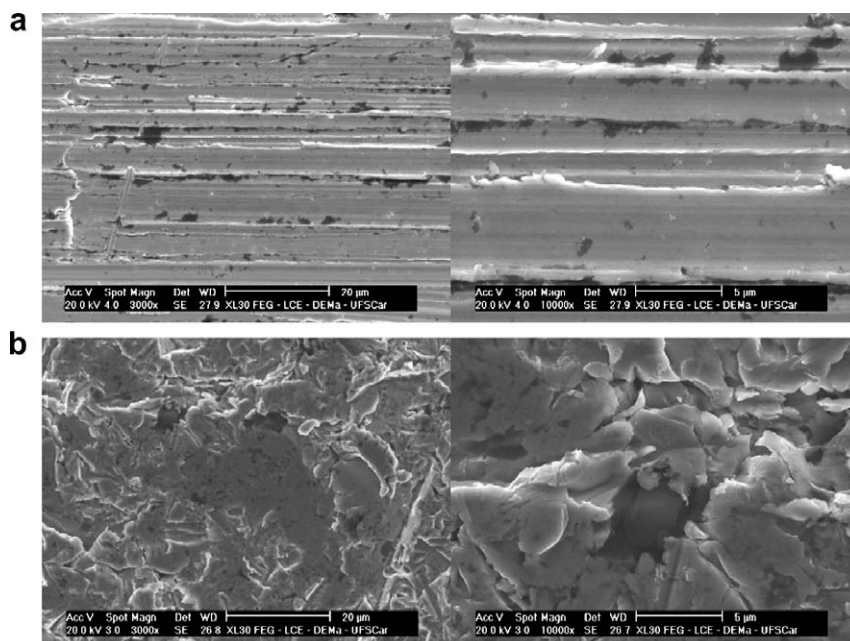


Fig. 3. Micro-photographs from a copper surface. (a) Sand paper scaled (SP), $R_a = 0.4 \mu\text{m}$; (b) shot pinned (SPI), $R_a = 1.9 \mu\text{m}$.

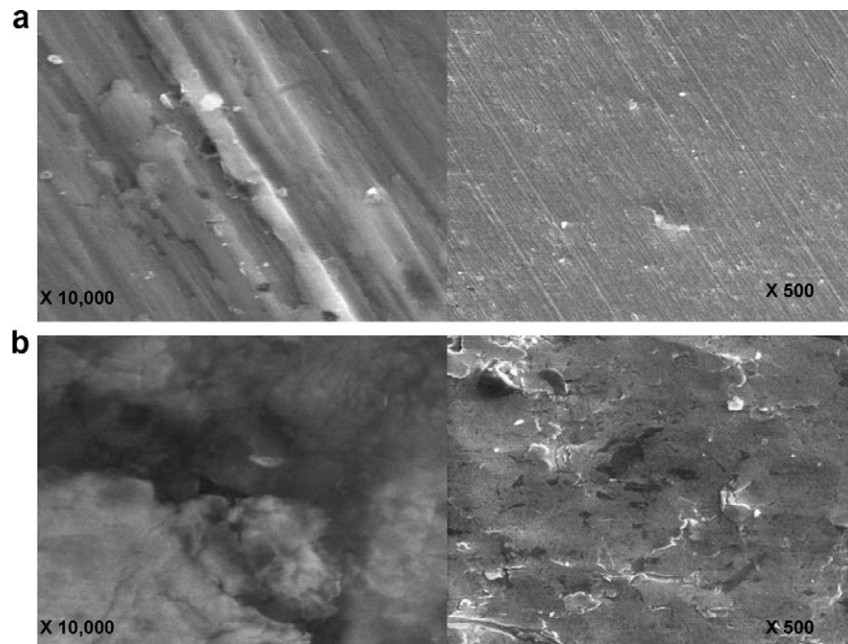


Fig. 4. Micro-photographs from a stainless steel surface. (a) Sand paper scaled (SP), $R_a = 0.04 \mu\text{m}$; (b) shot pinning (SPI), $R_a = 1.75 \mu\text{m}$.

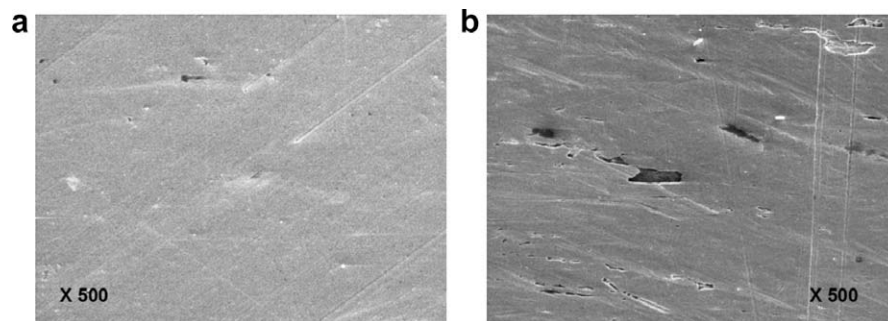


Fig. 5. Micro-photographs from stainless steel surfaces. (a) Polished (P), $R_a = 0.04 \mu\text{m}$; (b) commercial, $R_a = 0.36 \mu\text{m}$.

process produces a surface like the one shown in Fig. 3b. In this case, cavities instead of grooves are formed giving the surface a completely different aspect than the one obtained from the sand paper scaling process. Due to the copper ductility, the borders of grooves and cavities are very irregular with the presence of scraps that may eventually detach from the surface by the boiling action. Since stainless steel is less ductile, the finishing processes produce effects somewhat different from those in copper surfaces, as can clearly be noted in Fig. 4a and b. The cavities produced by the shot pinning process do not present the scraps and sharp edges noted in the copper surface. Similar results can be noticed in the scaled surface.

The effect of polishing a stainless steel surface is shown in the picture of Fig. 5a. A companion picture, Fig. 5b, has been included for comparison purposes with a commercial stainless steel surface. The grooves produced by the sand paper scale process, prior to the polishing procedure, can clearly be noted in the picture of Fig. 5a.

The effect of the size distribution of the glass micro spheres over the average roughness, R_a , of the brass surface is summarized in Table 3. Due to the different ductility of copper and stainless steel, different effects are obtained by the same size range of the glass

spheres. The resulting average roughness on the copper surfaces increases while in the stainless steel ones diminishes with respect to that obtained on the brass surface. The higher average roughness surfaces ($R_a > 4.0 \mu\text{m}$) have been sand blasted treated. As mentioned before, the sand was previously sieved to control the maximum particle size. The micro-characteristics of these surfaces have not been raised under the present investigation.

The surface finishing can be assessed by a statistical analysis of the roughness profile. The profile, the probability density function, and the normalized auto-correlation of different surfaces are shown in Fig. 6. The “y” value in this figure corresponds to the distance to the average line of the roughness peaks and valleys. It can

Table 3

Size range of glass beads used in the shot pinning of brass surfaces and the resulting value of R_a . Pressure of the feeding line: 10 bar; jet-surface distance: 100 mm.

Size range of particles (μm)	R_a (μm)
<63	1.2
106–212	1.8
212–600	3.0

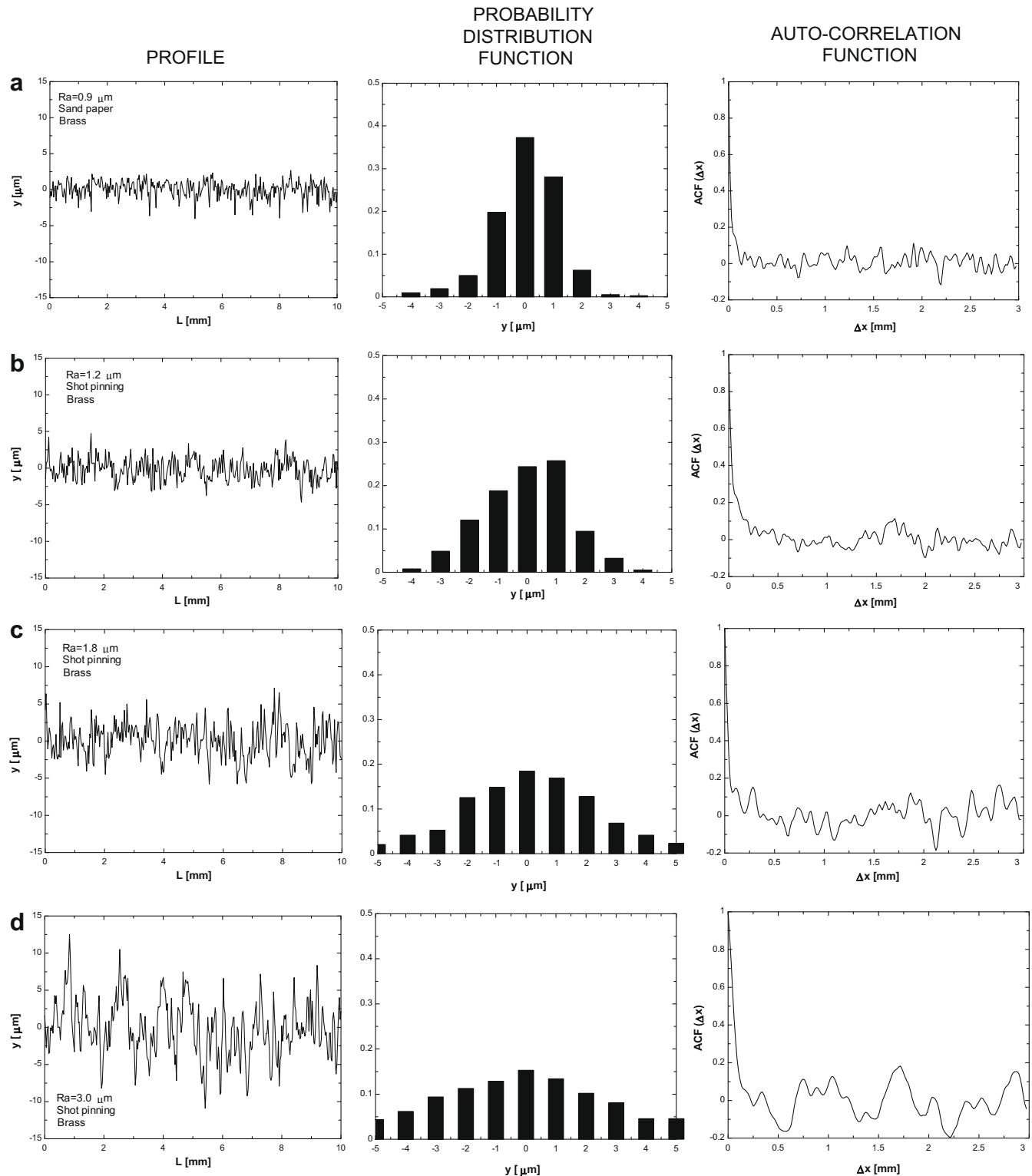


Fig. 6. Profile, probability distribution and auto-correlation function for different brass surfaces. (a) Scaled surface, $Ra = 0.9\ \mu\text{m}$; (b) shot pinned, $Ra = 1.2\ \mu\text{m}$; (c) shot pinned, $Ra = 1.8\ \mu\text{m}$; and (d) shot pinned, $Ra = 3.0\ \mu\text{m}$.

clearly be noted that the sand paper treated surface presents a dominance of a given cavity size range whereas the shot pinning presents a wider distribution of cavities. The probability distribution and the auto-correlation function clearly indicate that the range of cavities widens with the average roughness.

4. Results and analysis

The results reported in this paper involve two halocarbon refrigerants: R-123 and R-134a. The former is used in low pressure whereas the latter is typical of medium pressure applications.

Though the main thrust of the present investigation has been roughness effects, experiments with three different materials have been performed, thus the associated results will also be discussed and analysed.

4.1. Surface material

The effect of the heating surface material has been considered in a number of studies in the past, since the early classical paper by Rohsenow [21] to the more recent studies such as the ones by Gorenflo [8,22], Ribatski and Saiz Jabardo [23], Piore [24], and Stelute et al. [25]. In general, it has been recognized that the surface material affects nucleate boiling thermal performance, though it has been difficult to materialize this effect into workable correlations. Boiling heat transfer correlations have included this effect in different ways. Rohsenow [21] introduced the surface material effect indirectly through the combined surface/fluid coefficient, C_{sf} . Other correlations include this effect explicitly, through either a parameter involving physical properties of the material, Gorenflo [22], or a coefficient depending on the particular material, Ribatski and Saiz Jabardo [23]. Further on correlations will be used in assessing the significance of the present experimental results.

The effect of the surface material is shown in Fig. 7, where (h vs. q) refrigerants R-134a and R-123 data are plotted for two reduced pressures ($p_r = p/p_c$), 0.063 and 0.120. As expected, the heat transfer coefficient increases with the reduced pressure. This result confirms a trend that has been observed by several experimental investigations in the past. It must be added at this point that the effect of the reduced pressure on the heat transfer performance depends on both the material and the surface condition and finishing process. As a general rule, the higher the roughness the less sensitive to pressure is the heat transfer coefficient. In addition, polished surfaces heat transfer seem to be affected more by pressure than either scaled or shot pinned surfaces.

Thermal performance of brass surfaces is slightly better than that of the copper ones. However, stainless steel surfaces present a very distinct behavior as compared to the other two surface materials, their thermal performance being generally worst, especially at high heat fluxes. It is interesting to note in Fig. 7a–c that the thermal performance of stainless steel diminishes with respect to the other two materials as the roughness increases. This trend is the result of a combined effect of roughness and material over the nucleate boiling heat transfer coefficient [25,26].

It has been pointed out elsewhere in the past [20,25], that the slope of the (h vs. q) is affected by the surface material, a result that is confirmed by the plots of Fig. 7, especially when comparing the copper and brass results with those of the stainless steel surface. In order to further explore the effect of the surface material over the slope of the curve, let us approximate the relationship between the heat transfer coefficient and the heat flux by the following commonly used expression:

$$h = Cq^m \quad (2)$$

where the exponent “ m ” is related to the slope of the (h vs. q) curve. The exponent “ m ” has been obtained by linearly fitting data for heat fluxes higher than 2 kW/m² in order to warrant only boiling conditions, thus excluding natural convection effects. Variations of the slope “ m ” in the heat flux range of the present investigation have been neglected, since for most of the data it has been lower than 10%. The plot of Fig. 8 presents the slope “ m ”, in terms of the reduced pressure, fitted from R-123 data for the three surface materials considered herein and a surface roughness of 0.16 μ m. The results of Fig. 8 reflect those of Fig. 7, according to which the slope of the stainless steel surface is lower than that for copper and brass. In addition, the slope “ m ” diminishes with pressure, a result that confirms trends from the literature [8,9,20,22]. It must be observed that the range of reduced pressures in the present investigation is limited to that of the applications, as it is the case of the Fig. 8 for

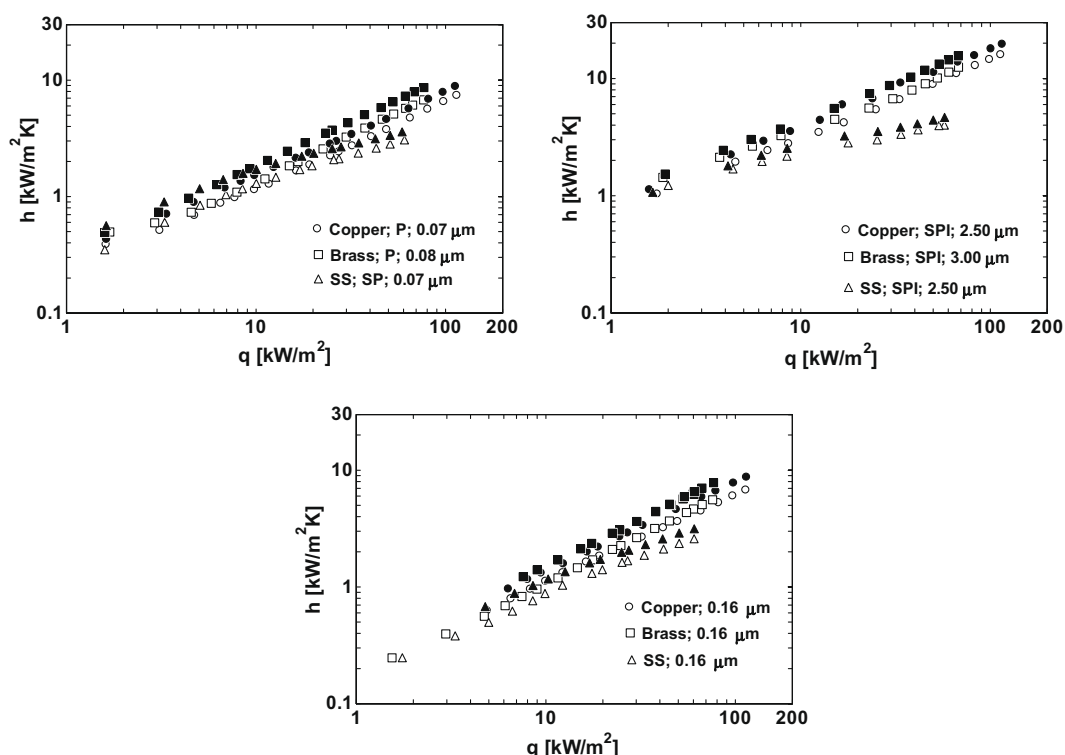


Fig. 7. The effect of the surface material over the rate of heat transfer. (a) R-134a, small surface roughness; (b) R-134a, high surface roughness; and (c) R-123, $R_a = 0.16 \mu$ m. Open symbols: $p_r = 0.063$; blackened symbols: $p_r = 0.120$.

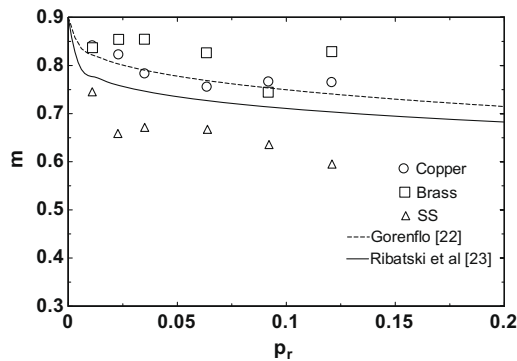


Fig. 8. Plot illustrating the effect of the surface material over the slope “ m ”. Refrigerant R-123, $Ra = 0.16 \mu\text{m}$.

refrigerant R-123. It must be stressed that some referenced authors have neglected the effect of pressure over the slope “ m ”, noteworthy Cooper [27] and Nishikawa et al. [28] who, respectively, proposed the following values: 0.67 and 0.8.

In order to assess the significance of the obtained results, data points of Fig. 8 have been overlaid in the same plot with the correlations proposed by Gorenflo [22] and Ribatski and Saiz Jabardo [23]. Gorenflo [22] proposed the following expression:

$$m = 0.9 - 0.3p_r^{0.3} \quad (3)$$

Later on Ribatski and Saiz Jabardo [23] fitted their experimental data with a similar correlation by changing the exponent of the reduced pressure from 0.3 to 0.2. Both correlations include the pressure effect but not the heating surface material. Whereas the Gorenflo correlation fits fairly well copper data, the Ribatski and Saiz Jabardo overestimates the value of “ m ” for stainless steel and underestimates it for copper and brass. It is interesting to note that the value proposed by Cooper [27] underestimates and the one by Nishikawa et al. [28] overestimates most of the data.

As a closing remark regarding the effect of the surface material, it must be noted that, for both refrigerants, copper and brass surfaces present close results regarding the heat transfer coefficient, though the brass surface performance is slightly better than the copper one. In contrast, the stainless steel results deviate significantly from those for copper and brass, presenting consistently lower heat transfer coefficients and slopes of the (h vs. q) curve. As a result, as suggested above, the dependency of the exponent “ m ” on the surface material might not be discarded in a general heat transfer correlation.

4.2. Roughness

It is a common belief since the early nucleate boiling research that the surface roughness affects positively the heat transfer coefficient. This trend is confirmed by the early research by Berenson [3] and Corty and Foust [29]. More recent investigations, like the ones conducted by Gorenflo and co-workers [8,22], and those by Nishikawa et al. [31], Luke [10,30], and Kang [7], confirm the trend according to which surface roughening tends to improve the heat transfer coefficient in nucleate boiling. Gorenflo [8,22] proposes the following explicit correlation for the effect of roughness in terms of the average surface roughness:

$$h \propto Ra^{2/15} \quad (4)$$

Luke [30] proposes a correlation for the explicit dependency of the heat transfer coefficient on the average surface roughness with the following general form:

$$h \propto Ra^{d-e \ln(p_r)} \quad (5)$$

In addition to include this explicit roughness dependence, Luke [30], based on experimental data for propane boiling on copper tubes of average roughness up to $11.3 \mu\text{m}$, suggested that the slope “ m ” is also affected both by the reduced pressure and the average roughness according to the following general expression:

$$m = a - bp_r^{0.37} + \frac{c}{1 + 200(Ra/Rao)^{10}} \quad (6)$$

where Rao is a reference roughness. Parameters “ a ”, “ b ”, “ d ”, and “ e ” from both of the Luke’s correlations are curve fitting constants. It can be noted that according to the Luke correlation, Eq. (6), average roughness increments reduce the slope “ m ”, a trend that is confirmed by the present results, as will be shown in the following paragraphs. However, Luke’s results display a continuous increment of the heat transfer coefficient up to the roughness of $11.5 \mu\text{m}$, a trend that is not confirmed by the investigation reported herein.

Present results confirm in part the trend related to the effect of roughness on the rate of heat transfer. The plots of Fig. 9a–d, developed from R-123 and R-134a data over a copper surface, illustrate the increment of the heat transfer coefficient with roughness. However, contrary to the common belief, the heat transfer coefficient increment is limited to a given range of surface roughness and heat fluxes. Beyond those ranges the heat transfer coefficient diminishes with roughness, as clearly seen in those plots. Some investigations from the literature confirm, at least qualitatively, the trend displayed in the plots of Fig. 9a–d. Kozitskii [31] obtained results from n -butane boiling in electrically heated stainless steel tubes with average roughness varying from $0.03 \mu\text{m}$ to $1.31 \mu\text{m}$. For pressures of 4.9 ($p_r = 0.129$) and 12.6 bar ($p_r = 0.332$), Kozitskii observed that the heat transfer coefficient diminishes when the average roughness of the surface is increased to $0.95 \mu\text{m}$ and $1.31 \mu\text{m}$. More recently, Benjamin and Balakrishnan [6] conducted experiments with several fluids (including water, n -hexane, and carbon tetrachloride) boiling on of aluminium and stainless steel surfaces with average roughness varying from $0.20 \mu\text{m}$ to $1.17 \mu\text{m}$. They also noted a heat transfer coefficient reduction with the increment of the average roughness above a certain value. In their review paper, Pioro et al. [9] suggest a possible reduction in the heat transfer coefficient for roughness beyond a certain limit. Finally, Corty and Foust [29] and Kurihara and Myers [32] data clearly point to the occurrence of a roughness limit regarding the effect over the rate of heat transfer.

The following are a summary of the conclusions that can be drawn from the results of Fig. 9:

- (1) The results of Fig. 9a–d clearly display two main ranges of roughness effects: the low range, encompassing average roughness up to around $3.0 \mu\text{m}$, and the high range, for surface average roughness higher than $3.0 \mu\text{m}$. Unfortunately, only one two average roughness in the high range have been tested, $4.6 \mu\text{m}$ and $10.5 \mu\text{m}$, what makes the above suggested limits of roughness ranges sketchy. However, they have been considered useful for the current analysis purposes.
- (2) The plots of Fig. 9a and b for refrigerant R-123 clearly show that the heat transfer coefficient increases with the average roughness in the low range. The effect of the surface roughness over the heat transfer coefficient is characterized by an opposite trend in the low heat flux range (lower than 15 kW/m^2) for the roughness high range, from $3.30 \mu\text{m}$ to $10.5 \mu\text{m}$.
- (3) The plots of Fig. 9c and d for refrigerant R-134a display trends similar to those for the refrigerant R-123. Present results clearly indicate that the heat transfer coefficient might even diminish with the surface roughness in the high range.

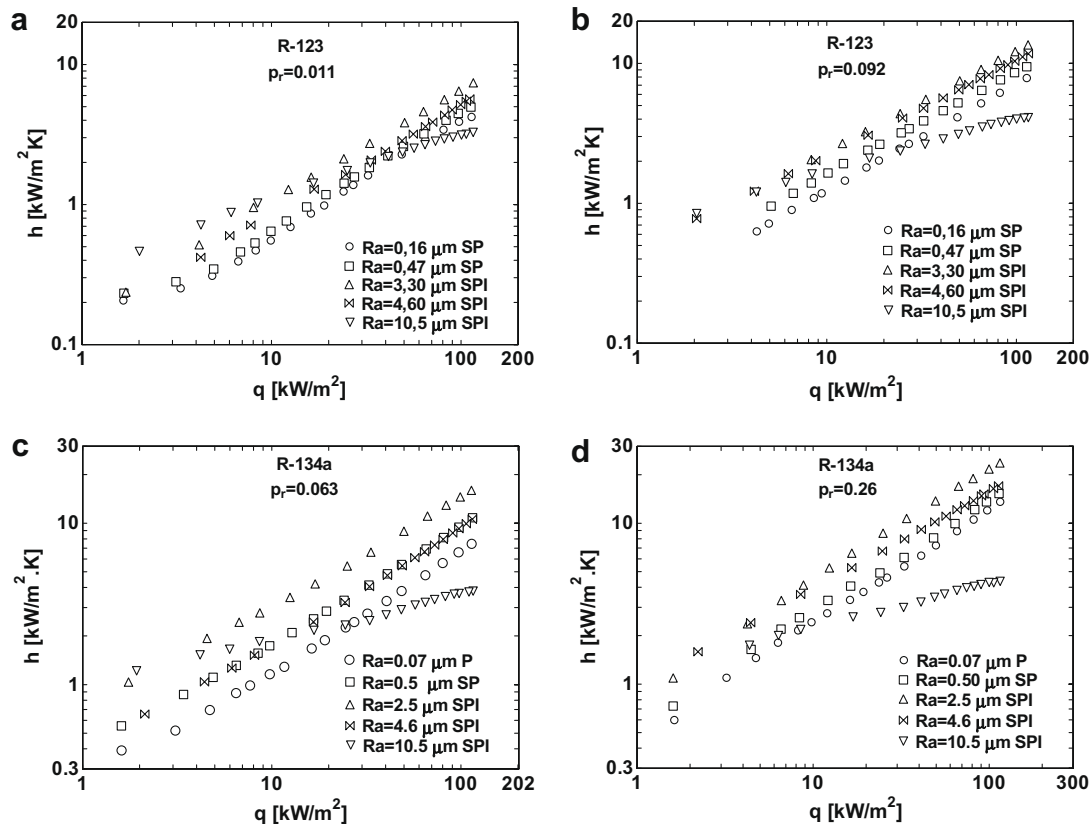


Fig. 9. The effect of surface roughness on the heat transfer coefficient for a copper heating surface (a) R-123, $p_r = 0.011$; (b) R-123, $p_r = 0.092$; (c) R-134a, $p_r = 0.063$; and (d) R-134a, $p_r = 0.260$.

- (4) The 10.5 μm roughness boiling curve can be divided into two heat flux ranges, delimited by a heat flux of around 15 kW/m^2 . In the low heat flux range, the heat transfer coefficient is highest among all the roughness covered in the present investigation. This is a rather unusual trend, reported in the literature only for enhanced heat transfer tubes [33] and not for plain tubes. A general conclusion regarding highly shot pinned roughened boiling surfaces is that they are potentially interesting for low heat flux applications such as the refrigerating ones.
- (5) Average roughness for the other two surface materials, brass and stainless steel, has been limited to values lower than 3.5 μm and 3.20 μm , respectively. Data for refrigerant R-134a boiling on these two surface materials is presented in Fig. 10a–d. It can be noted that the observed trends for copper are generally confirmed in this case. The observed trend toward a limit on the roughness effect suggested by Kurihara and Myers [32] is clearly observed in those plots.
- (6) The results for stainless steel of Fig. 10c and d are noteworthy since they display a lessen effect of the surface roughness over the heat transfer coefficient. This trend is strengthened at higher reduced pressures, as can be concluded by comparing Fig. 10c with Fig. 10d.

The effect of the roughness over the slope of the (h vs. q) curve could be outlined from the plots of Figs. 9 and 10. In order to better visualize this effect, curve fitted values of “ m ” for the copper surface have been plotted against the reduced pressure for different roughness values and refrigerants. The resulting plot is shown in Fig. 11a and b. In general, “ m ” diminishes with roughness though the effect might be different, depending on the refrigerant. In the lower roughness range, the effect of roughness is more significant

in R-123 than in R-134a. The slope “ m ” diminishes significantly for both refrigerants for the surface roughness of 10.5 μm with respect to the other values of roughness, attaining values outside the typical range, which varies from 0.5 to 0.8.

The curves representative of the correlations for the slope “ m ” by Gorenflo [22], Eq. (3), and Ribatski and Saiz Jabardo [23] have been overlaid with experimental data in the plots of Fig. 11. It can be noted that both correlations reproduce reasonably well the trend in the low range of roughness. However, from the quantitative point of view the Ribatski and Saiz Jabardo correlation seems best fitted to the present data than the one proposed by Gorenflo. As expected, both correlations over predict experimental data corresponding to the high roughness range.

Most of the average roughness values provided by the different roughening procedures are not close enough to allow for a significant thermal performance comparison between them. However, some cases can be used for a sound comparison. This is the case of stainless steel data which present average roughness values of 0.03 μm for polished and 0.04 μm for scaled surfaces. Data for both roughening procedures are shown in the plot of Fig. 12a. It can be noted that differences are minimal, with the polished surface presenting a slightly better performance. Thus, as a first approximation, it can be concluded that polished surfaces present better performance, a result in accordance with Berenson [3] conclusions.

The closer average roughness values between sand paper and the shot pinning surfaces are 0.9 μm and 1.2 μm , obtained for a brass surface. Data for this case is plotted in Fig. 12b. It can be noted that though the shot pinning surface presents a slightly better performance, its average roughness is also higher, what makes a conclusion difficult to draw regarding the effect of the roughening procedure.

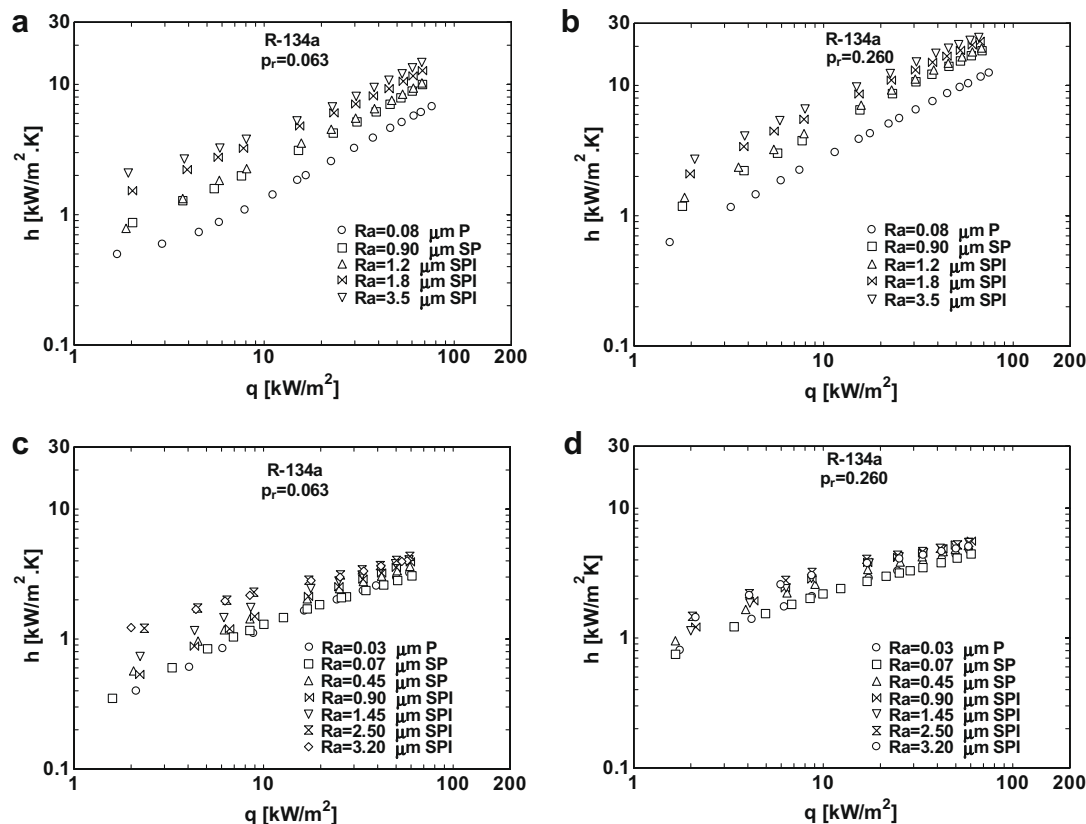


Fig. 10. The effect of surface roughness on the heat transfer coefficient for a brass and stainless steel heating surfaces (a) Brass, R-134a, $p_r = 0.063$; (b) brass, R-134a, $p_r = 0.260$; (c) SS, R-134a, $p_r = 0.063$; (d) SS, R-134a, $p_r = 0.260$.

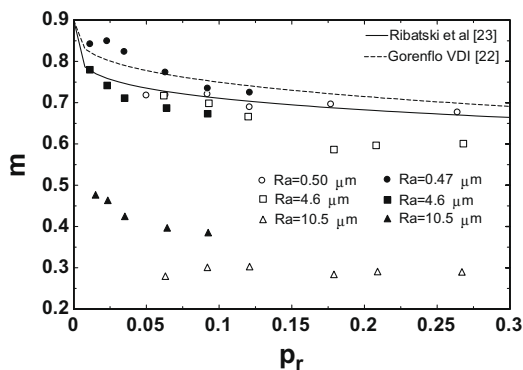


Fig. 11. Variation of the exponent “ m ” with the reduced pressure for different values of the heating surface roughness. Blank symbols: R-134a; blackened: R-123.

Results from the literature are not conclusive regarding the effect of the surface treatment procedure [9]. Data from the present investigation do not allow drawing any definitive conclusion neither. It must be stressed that in the present investigation the sand paper treated surfaces present circumferential grooves, which apparently seem not to cause major differences in boiling thermal performance as compared with the shot pinned grooves of similar average roughness.

As a final remark regarding the roughness effects on the boiling thermal performance, it would be interesting to speculate over the observed trends in the present investigation. The heat transfer coefficient increment with the heat flux is closely related to the population of active cavities on the heating surface. The enhancement of the nucleate boiling thermal performance by the roughen-

ing of the heating surface is generally attributed to the growth of the population of active cavities promoted by rougher surfaces as a result of the increment of both the size and the range of sizes of the cavities. This trend is in agreement with conventional nucleation criteria from the literature, Hsu [34]. According to these criteria, the size range of active cavities widens with the surface superheating. Roughening the surface would increase the range of available cavity sizes, allowing for the increment of active cavities for a given surface superheat. However, as the size of cavities increases, eventually the larger cavities might be filled with liquid, not being available for activation, Pioro et al. [9], Kozitskii [31]. In the present case, surfaces in the high range of roughness present a wider range of cavities available for activation at low heat fluxes what tends to increment the heat transfer coefficient with respect to less rougher surfaces. However, as the surface superheat increases, sites available for activation seem to diminish with respect to those available on smoother surfaces due to the excessive size of the cavities. A detailed analysis of the micro-structure of the surface would be needed in order adequately interpret the observed trend in the high range of surface roughness, as suggested by Luke [30]. The analysis should include the effect of the roughening procedure and the wettability of the surface by the boiling liquid.

5. Comparison with correlations

Along the years of nucleate boiling research a number of correlations have been proposed to predict the heat transfer coefficient. Some have treated the problem under the point of view of objective curve fitting experimental data, being expressed as a function of reduced properties instead of actual transport properties. Two of these correlations, previously mentioned, based on similar argu-

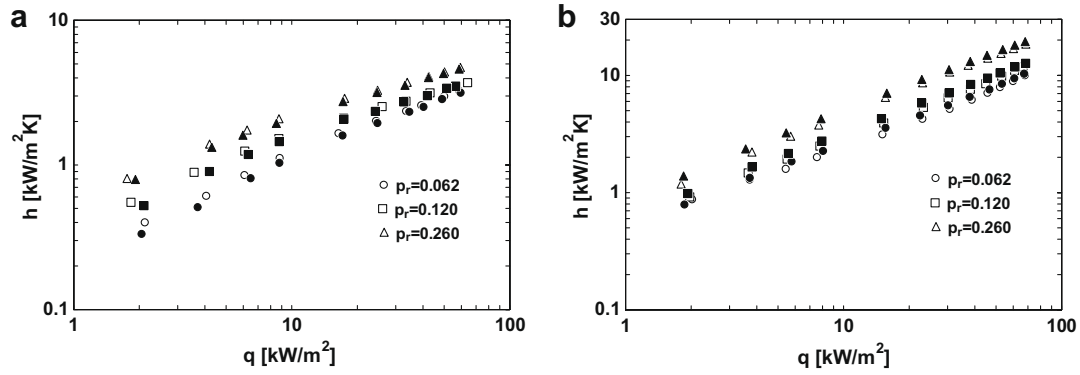


Fig. 12. Refrigerant R-134a boiling thermal performance comparison between different roughening procedures. (a) Stainless steel surface: P blank ($R_a = 0.03 \mu\text{m}$) vs. SP blackened ($R_a = 0.04 \mu\text{m}$); (b) brass surface: SP blank ($R_a = 0.90 \mu\text{m}$) vs. SPI; blackened ($R_a = 1.2 \mu\text{m}$).

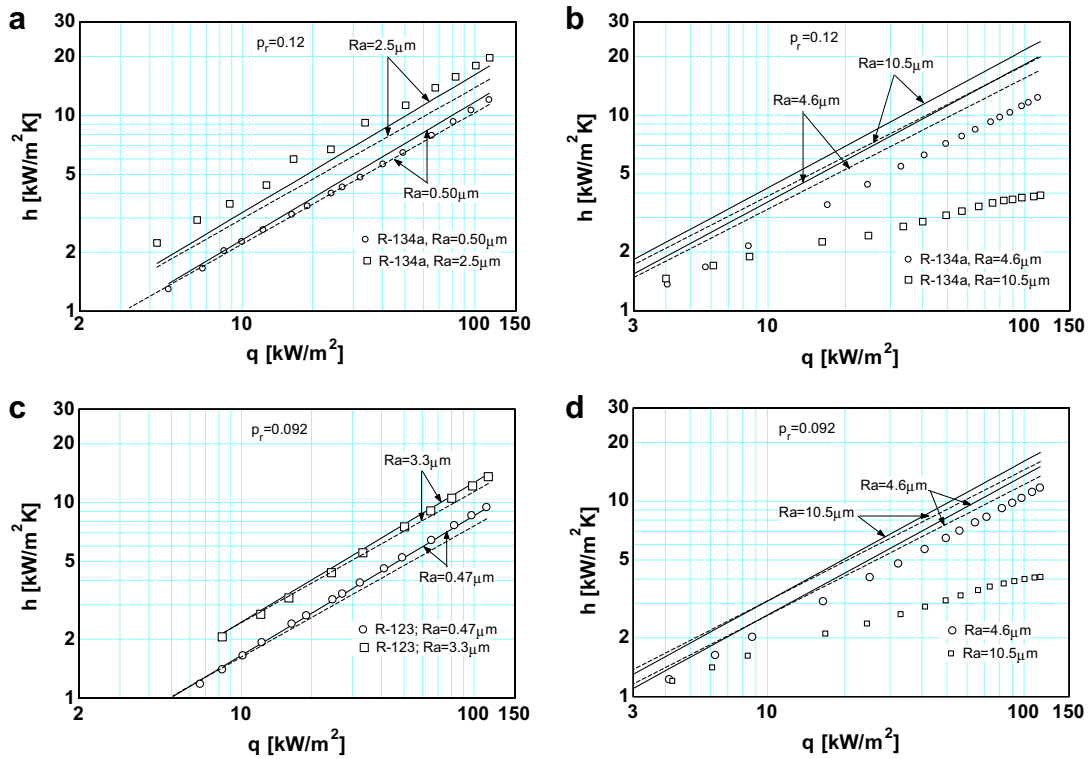


Fig. 13. Variation of the heat transfer coefficient with the heat flux. (a) Refrigerant R-134a; $p_r = 0.12$, $R_a = 0.5 \mu\text{m}$ and $2.5 \mu\text{m}$; (b) refrigerant R-134a; $p_r = 0.12$, $R_a = 4.6 \mu\text{m}$ and $10.5 \mu\text{m}$; (c) refrigerant R-123; $p_r = 0.092$, $R_a = 0.47 \mu\text{m}$ and $3.3 \mu\text{m}$; and (d) refrigerant R-123; $p_r = 0.092$, $R_a = 4.6 \mu\text{m}$ and $10.5 \mu\text{m}$. Continuous line: Ribatski and Saiz Jabardo [23]; broken line: Cooper [27].

ments, will be considered for the purpose of assessing the significance of the present data and to evaluate their performance in predicting the heat transfer rate in the range of roughness values and materials considered herein. The first is the one proposed by Cooper,

$$h = 55q^{0.67} p_r^n (-\log_{10} p_r)^{-0.55} M^{-0.5} \quad (7)$$

where the exponent “ n ” is a function of the roughness parameter, R_p

$$n = 0.12 - 0.2(\log_{10} R_p) \quad (8)$$

Cooper suggests correcting the numerical coefficient of his correlation by a factor of 1.7 for cylindrical copper surfaces. It has been found that the use of the suggested correction would result in a significant overprediction of the current experimental data.

As a result, this correction has been omitted in the present analysis. The present data have been evaluated based on the average surface roughness, R_a , whereas the Cooper correlation includes the parameter, R_p , as in Eq. (8). There is some debate regarding the relation between these roughness parameters. However, for the present analysis purposes, the following straightforward expression suggested by Gorenflo [22] has been used:

$$R_a = 0.4R_p \quad (9)$$

As already observed, Cooper assumes that the exponent of the heat flux is constant and equal to 0.67.

Ribatski and Saiz Jabardo [23] suggested the following alternative expression, according to which the exponent “ m ” of the heat flux, given by Eq. (3), depends only on the reduced pressure:

$$h = f_p q^m p_r^{0.45} (-\log_{10} p_r)^{-0.80} Ra^{0.2} M^{-0.5} \quad (10)$$

f_p is a surface material parameter, which assumes the following values: 100 for copper, 85 for stainless steel, and 110 for brass.

The plots of Fig. 13a–d illustrate the behavior of both correlations for refrigerants R-134a and R-123 boiling on copper surfaces of roughness in the low and high ranges for reduced pressures of 0.12 and 0.092, respectively. Both correlations perform reasonably well for the low roughness, with deviations within the uncertainty of experimental results, especially for the lower roughness surface and refrigerant R-123. However, their performance tends to deteriorate for the higher roughness, overpredicting the experimental results, especially at 10.5 μm . This is an expected trend since both models predict the increment of the heat transfer coefficient with the average roughness of the surface.

A general conclusion regarding nucleate boiling heat transfer coefficient correlations is that their use must be limited to the low range of surface roughness. Their extension to higher roughness values is not recommended due to the observed trend according to which the heat transfer coefficient attains a maximum at a given surface roughness. In addition, it must be stressed that the effect of surface roughness on the slope “ m ” of the heat flux must also be taken into consideration, as previously suggested.

6. General conclusions

The following are remarks that summarize the results from the present investigation:

- (1) The heat transfer coefficient is affected by the surface roughness in a conventional manner in the standard roughness range. However, it has been observed a trend shift at high values of the surface roughness, affecting both the heat transfer coefficient and the slope of the curve (h vs. q), characterized by the exponent “ m ” of Eq. (2).
- (2) As expected, both the heating surface material and the boiling liquid also affect the heat transfer coefficient.
- (3) The slope related exponent “ m ” is within the typical range for the low range of average roughness. However, for larger roughness values, the slope diminishes attaining values of the order of 0.3 for the surface roughness of 10.5 μm , a level way out of the typical range.
- (4) Very rough surfaces tend to present better boiling thermal performance than smoother ones at low heat fluxes, the trend shifting in the high heat flux range.
- (5) Care must be exercised in using nucleate boiling correlations for rough surfaces due to their inadequate prediction of the roughness effect.

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