Heat transfer at boiling of refrigerants in channels with twisted tape insert

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Abstract. The paper presents the review results of heat transfer at boiling in channels with twisted tape inserts. Various methods and approaches to the research of heat transfer processes at boiling of refrigerants in channels with twisted tape inserts were identified, a significant difference of the influencing factors on the heat transfer depending on the range of regime parameters under study was noted and also the necessity for research in this field was shown.

1. Heat transfer at boiling of refrigerants in channels with twisted tape inserts

The flow swirling is one method of heat transfer enhancement. The flow swirling in channels can be organized by various means: coils, tangential inlet, screws, spiral inserts, inserts in the form of twisted tapes and profiled cuttings of the channel walls. However, in the literature the twisted tapes are of the greatest interest (figure 1) since they are easy to manufacture and these inserts can be applied in the modernization of already operating heat exchangers for which reason a lot of works in the native and foreign literature are devoted to the heat transfer research at forced convection and bubble boiling in channels with twisted tape inserts [1-3].

Recently, together with studies of classical twisted tapes much attention was paid to twisted tapes of modified geometry [4-6].

In [4-6] a wide review of twisted tapes with various geometries is presented.

These are the twisted tapes with perforations, various cutouts and a cutout central part, bent segments, split tapes, twisted tapes with a periodic variation of twisting along the length, twisted tapes with fins installed against the twisting direction on its surface [5, 7].

Figure 1. Classical twisted tape.
The limited studies of heat transfer in channels with the above-mentioned twisted tapes of various geometries were carried out under forced convection of the coolant. The authors of these studies note an increase of the heat transfer coefficient and hydraulic resistance in channels with modified twisted tapes compared with twisted tapes of classical geometry, especially in the laminar region [5] as well as authors are unison in opinions that the complex mechanism of flow interaction with the modified generator of the twisted tape influences on the flow structure and indicate the need to search for optimal geometric parameters in further studies.

At a review of literature available in the open access it was found that the studies of heat transfer at boiling of fluids in channels with flow swirling were carried out only with the use of classical twisted tapes having different relative pitches of twist s/d [2, 7-15] at flow of coolant, water and liquid nitrogen. In most of the studies the halohydrocarbon refrigerants were used as a working fluid at the horizontal configuration of the working section using the electric heating. The experiments were carried out for tapes with relative pitches of twist s/d from 2.5 to 15 for tube diameters d from 3.8 to 15.9 mm made of stainless steel and aluminum at low mass velocities \( \rho_w \) less than 350 kg/(m²s).

So in [14] based on their own experimental data at boiling of halogen refrigerants in channels with twisted tape inserts with a relative pitch of twist s/d=4.15 a dependence to determine the heat transfer coefficient (1) was proposed, the authors state that the deviation of the experimental data of a similar work [15] from the values calculated by the equation (1) is 30-40%.

\[
Nu = 1.356Sw^{\alpha_1}Pr^{\alpha_2} \left( \frac{P}{P_{\text{critical}}} \right)^{\alpha_3} [-\ln(\text{Pr})]^{\alpha_4}Bo^{\alpha_5};
\]

where:
\[
\begin{align*}
\alpha_1 &= 0.993 - 1.181x + 0.899x^2; \\
\alpha_2 &= 1.108 - 2.366x + 1.451x^2; \\
\alpha_3 &= -2.383 + 5.255x + 1.791x^2; \\
\alpha_4 &= -3.195 + 6.668x; \\
\alpha_5 &= 1.073 - 2.679x + 1.443x^2; \\
\end{align*}
\]

\[
Sw = \frac{Re_s}{\sqrt{y}}; \quad Re_s = Re \sqrt{\frac{1 + \left( \frac{\pi s}{2y} \right)^2}{1 - 4\delta/\pi d}}.
\]

In [11] an experimental study of the heat transfer at boiling of R134a in channels with an internal diameter \( d=7.5 \) mm with twisted tape inserts with relative pitches of twist s/d=6, 9, 12, 15 at mass velocities \( \rho_w=54, 85, 114, 136 \) kg/(m²s) was carried out. The authors in [11] noted a change of the heat transfer coefficient from 0.8 to 1.7 times. The greatest increase of the heat transfer was recorded in a channel with a twisted tape having the smallest relative pitch of twist s/d=6 at a vapor content \( X=0.4-0.6 \) and mass velocity \( \rho_w=54-85 \) kg/(m²s) it is explained by the fact that in the region of these parameters in the channel without an insert (tape) the wave flow regime is observed. The installation of tape changes the wave flow regime to the annular one. At a mass velocity \( \rho_w=136 \) kg/(m²s) the flow structure always remains annular and the installation of tapes at low vapor content does not lead to a significant change in the heat transfer coefficient when changing the relative pitch of twist \( s/d \) from 15 to 6 the heat transfer increase is 24% and at lower velocities 11-15%. The results of the experimental data comparison with the values calculated by the dependence (1) are in the range from -65% to +25%. In connection with this in [11] the following dependence (2) was proposed based on the Agrawal and Varma (3) criterial model [15]:

\[
\frac{h_{tt}}{h_{pt}} = 0.0056Re_s^{2.214}Bo^{1.532}y^{-0.5} + 1.2156;
\]
where, $h_{pt}$ — calculation by the Gyngor and Winterton method [16].

$$
\frac{h_{tt}}{h_{pt}} = 0.002944 Re_0^{0.247} Bo^{1.624} y^{-0.5219}.
$$

(3)

The correlation (2) describes the experimental data [11] within an error of $\pm 25\%$. In [10] the experimental data on the heat transfer at boiling of refrigerant R134a in channels with twisted tape inserts was compared with the Jensen-Bensler method (4) [12], dependence (4) is a modification of Chen’s method [17]:

$$
h_{tt} = S h_{NB} + F h_c;
$$

(4)

$h_{NB}$ — Calculation according to the Forster-Zuber equation:

$$
h_{NB} = 0.00122 \left(\frac{\lambda_f^{0.79} C_p^{0.45} \rho_f^{0.49} g^{0.25}}{\sigma^{0.5} \mu_f^{0.29} \rho_f^{0.24} \rho_g^{0.24}}\right) \Delta T_s^{0.24} \Delta p_s^{0.75};
$$

(5)

where $S$ — bubble boiling suppression ratio proposed by Bennett et al. [18]:

$$
S = \left(\frac{\lambda_f}{\alpha F X_0}\right) \left[1 - \exp\left(-\alpha F X_0\right)\right];
$$

(6)

$$
X_0 = 0.041 \left[\frac{g \rho_s \sigma}{g(\rho_f - \rho_g)}\right]^{1/2} ;
$$

(7)

for $\frac{1}{\chi} \leq 0.1 F = 1.0$; for $\frac{1}{\chi} > 0.1 F = 2.35 \left(\frac{1}{\chi} + 0.213\right)^{0.736}$.

It is shown that the experimental data deviation from those calculated by dependence (4) is $-60\%$ to $+30\%$. Dependence (4) was obtained as a result of experimental data processing at boiling of refrigerant R113 under vertical configuration of channels with internal diameter $d=8.1$ mm and $d=13.92$ mm, refrigerant mass velocities $\rho_w=120$ and 1600 kg/(m²s), heat flow densities $q=0-50$ kW/m² while the experimental data bank [11] was obtained at boiling of refrigerant R134a in a horizontal channel with internal diameter $d=7.5$ mm, relative pitches of twist $s/d=6-15$ refrigerant mass velocity $\rho_w=54-136$ kg/(m²s), heat flow densities $q=1.8-5.3$ kW/m², the authors of [10] do not recommend to use the dependence (4) to determine the heat transfer coefficient at boiling of refrigerant R134a.

Yu.V. Mineev in [13] showed that when heavier fluid particles are thrown to the tube wall because of the centrifugal force there is an improvement in the fluid irrigation of the tube internal surface which consequently leads to a substantial (compared to the smooth tube) increase of the heat transfer coefficient. Thus, for $q=1.5-2$ kW/m² and a decrease of the relative pitch of twist in the studied range ($(0<d/s<0.059)$ the heat transfer coefficient $\alpha$ increased by an average of 1.5-1.7 times while at $q<1.5$ kW/m² this value was 2 and more. At small $q$ values the intensity of the heat transfer mechanism caused by the evaporation process is negligibly small in comparison with the intensity of the convective heat transfer which is in turn determined by the flow velocity. In [13] an empirical dependence (8) to calculate the heat transfer coefficient was obtained on the basis of the experimental study results on the boiling of refrigerant R407C inside a tube with tape turbulizers:

$$
\alpha = 5.59 \rho_w^{0.56} q^{0.6} (d/s)^{0.13} p^{0.21} \beta^{1.13};
$$

(8)
The application domain of this dependence: \( \rho v = 32-150 \text{ kg/(m}^2\text{s)}; \  q = 0.5-4 \text{ kW/m}^2; \ d/s = 0.03-0.06; \  P = 0.22-0.32 \text{ MPa}; \ \beta = 0.1-0.9; \ \text{working medium – R407C}. \)

As a processing result of his own experimental data [13] and data of other authors [19, 20] the dependence (9) to calculate the heat transfer in a tube enhanced by the tape turbulizers under the condition of complete wetting was proposed:

\[
Nu = 0.05 Re^{0.33} Pr^{0.43} De^{0.27} Pe^{0.6} Kp^{0.2}; \tag{9}
\]

where: \( Kp = Pd/\sigma \) – complex determining the pressure influence at boiling.

The application domain of the dependence (9): \( Re = 1000-17000; \ De = 100-300; \ Pr = 2.5-7; \ Kp = 0.2-0.33; \ Pe = 33-190 \). It is noted that the dependence (9) can also be used to determine the heat transfer coefficient in channels with twisted tape inserts at various design parameters of twisting \( s/d \) and tube diameters \( d \) this is also confirmed by comparing the experimental studies results on heat transfer at two-phase swirled flows [19,20]. It is claimed that the use of tape inserts leads to a substantial increase of the heat transfer coefficient (up to 1.8 times) especially at a small pitch of turbulizer \( (d/s = 0.126) \) and high values of the true volumetric vapor content which correspond to the stratified flow regime. In [13] it is noted that an increase of the mass flow rate \( \rho w \) causes an increase of the heat transfer coefficient \( \alpha \) which is less significant compared to a smooth tube because of the convective heat transfer enhancement, the degree of influence is on the average 0.56. At small values of the heat flow the intensity of the heat transfer mechanism caused by the evaporation process is negligibly small in comparison with the intensity of the convective heat transfer which is in turn determined by the flow velocity.

In [21] the experimental study of heat transfer at boiling of refrigerant R134a in the channels with smooth and modified (fins installed on the tape surface) twisted tape inserts with a relative pitch of twist \( y = s/d = 3; 4; 6 \), pitch of fin installation \( t = 60; 40; 20 \text{ mm}, \) at fixed values of the fin height \( h = 1 \text{ mm} \) and installation angle \( \phi = 45^\circ \) was carried out in the range of the regime parameters: Reynolds number according to the fluid circulation velocity \( Re_0 = 30000-85000 \), heat flow density \( q = 99-250 \text{ kW/m}^2 \), the estimated mass flow vapor content according to the supplied heat flow at the outlet of the working section reached \( X = 0.07-0.55 \). The comparison results of the experimental data with the values calculated by the dependence (10) are presented, according to this comparison the maximum deviation of the experimental data from the calculated ones by the obtained dependence (10) is \( \pm 15\% \) with a confidence probability of 0.95.

\[
Nu = 10.33Re_0^{0.7} Kp^{0.2} (s/d)^{-0.15} Pr^{0.43} \tag{10}
\]

A greater influence on the change of the wall temperature is exerted by the thermal load applied to the working section. The Reynolds number in the range \( Re_0 = (3.1-8.3) \times 10^4 \) at \( q = \text{const} \) does not influence on the change of the wall temperature. This indicates the prevailing influence of the evaporation mechanism. In the work of A.V. Dedov [8] on heat transfer at bubble boiling of water in channels with twisted tape inserts under conditions of one-sided heating at a pressure \( P = 1.0 \) and \( 2.0 \text{ MPa} \), mass velocity \( \rho w = 350-11300 \text{ kg/(m}^2\text{s}) \) it is noted that at mass velocities less than \( 2200 \text{ kg/(m}^2\text{s}) \) the heat exchange regimes with the predominant influence of bubble boiling mechanisms when heat transfer coefficient is practically independent of the flow velocity [22] are realized.

In [9-11, 13, 15] it is noted that flow velocity at boiling of refrigerants in channels with twisted tape insert has influence at Reynolds numbers \( Re_0 < 17000 \) (\( \rho w = 32-150 \text{ kg/(m}^2\text{s}) \)) and according to different data is in the range of 0.33 to 2.247. It is important to note that these results were also obtained for lower heat flow densities \( q < 50 \text{ kW/m}^2 \) [9-11, 13, 15] in contrast to these works the results obtained in [21] significantly exceed the range of the regime parameters compared to the earlier obtained ones.
2. CONCLUSION

When analyzing the data of the literature review it is established that the heat transfer and hydrodynamic processes in channels with (classical) twisted tape inserts at the single-phase flow of the working medium are now well studied. The generalizing dependencies to calculate the heat transfer and hydraulic resistance are obtained. There is a tendency to increase the works on the studies of heat transfer and hydrodynamics in channels with various modifications of the twisted tapes geometry at the forced convection; however the range of the studied regime parameters, geometries and working mediums is very limited, the authors of [4-6] note the necessity for additional studies.

The works on the study of the heat transfer at boiling of fluid in channels with flow swirling were carried out only with application of classical twisted tapes [2, 7-15] in most of which the halohydrocarbon refrigerants were used as a working fluid at the horizontal configuration of the working section using the electric heating for the tapes with relative pitches of twist $s/d$ from 2.5 to 15 for tube diameters $d$ from 3.8 to 15.9 mm made of stainless steel and aluminum at low mass velocities and low heat flow densities $q_{lw}$ less than 350 kg/(m$^2$s) and $q$=kW/m$^2$, respectively.

Works on the study of the heat transfer at boiling of fluids in channels with inserts in the form of modified twisted tapes in a wide range of regime parameters are practically absent.

References

[1] Smithberg E and Landis F 1964 Friction and Forced Convection Heat Transfer Characteristics in Tubes with Twisted Tape Swirl Generators J. Heat Trans., 86, pp 39–49.
[2] Lopina R F and Bergles A E 1969 Heat Transfer and Pressure Drop in Tape Generated Swirl Flow of Single-Phase Water J. Heat Trans., 91, pp.434–42.
[3] Date A W and Singham J R 1972 Numerical Prediction of Friction and Heat Transfer Characteristics of Fully Developed Laminar Flow in Tubes Containing Twisted Tapes ASME-72-HT-17, ASME, New York. Vol. 17. pp. 72.
[4] Popov I A, Makhyanov Kh M and Gureev V M 2009 Physical basis and industrial application of heat exchange enhancement / under the general editorship of Yu F Gortyshov (Kazan Center for Innovative Technologies) p 560.
[5] Giniyatullin A A 2015 Heat transfer and hydraulic resistance of tubes with inserts in the form of the finned twisted tapes Ph.D. thesis in Eng. Sci. 01.04.14 Kazan p 268.
[6] Nithiyesh C Kumar and Murugesan P 2012 Review on Twisted Tapes Heat Transfer Enhancement Int. J. of Sci. & Eng. Research 3, Vol. 3, Issue 4.
[7] Abdrahnov A R, Karpova O B, Tarasevich S E and Shchukin V K 1994 Mathematical model and results of experimental investigation of heat exchange of cryogent swirl boiling flow Proc. X Int. Heat Trans. Conf. (Brighton) vol 7 p 409-14.
[8] Dedov A V, Komov A T, Varava A N and Yagov V V 2010 Hydrodynamics and heat transfer in swirl flow under conditions of one-side heating. Part 2: Boiling heat transfer. Critical heat fluxes. Int. J. of Heat and Mass Trans. 53 Iss. 21-22, pp 4966-75.
[9] Kanizawaw F T, Mogaji T S and Ribatski G 2016 A new model for flow boiling heat transfer coefficient inside horizontal tubes with twisted-tape inserts Int. J. of refrigeration 61 pp 55–68.
[10] Mogaji T S, Kanizawa F T, Ribatski G and Bandarra Filho E P 2012 Experimental study of the effect of twisted-tape inserts on flow boiling heat transfer enhancement and pressure drop penalty Int. J. of refrigeration XXX pp 1–12.
[11] Akhavan- Behabadi M A, Kumar R, Mohammadpour A and Jamali-Astbiani M 2009 Effect of twisted tape insert on heat transfer and pressure drop in horizontal evaporators for the flow of R-134a Int. J. of Refrigeration XXX, pp 1–9.
[12] Jensen M K and Bensler H P 1986 Saturated forced-convective boiling heat transfer with twisted-tape inserts J. Heat Transf. 108 pp 93–9.
[13] Mineev Yu V 2007 Hydrodynamics and heat transfer at boiling of mixture refrigerant r407c inside the tube with tape turbulizers Ph.D. thesis in Eng. Sci. 01.04.14 Astrakhan p 202.
[14] Kedzierski M A and Kim M S 1998 Convective boiling and condensation heat transfer with a twisted tape insert for R12, R22, R152a, R134a, R290, R32/R134a, R32/R152a, R290/R134a, R134a/R600a *Therm. Sci. Eng.* 6(1) pp113–22.

[15] Agrawal K N and Varma H K 1986 Heat transfer during forced convection boiling of R-12 under swirl flow *J. Heat Trans.* 108 pp 567–72.

[16] Gungor K E and Winterton R H S 1987 A general correlation for saturated flow boiling and comparison of correlations with data *Chem. Eng. Res. Des.* 65 pp 148–56.

[17] Chen J C 1963 A Correlation for Boiling Heat Transfer to Saturated Fluid in Convective Flow *ASME Paper* 63-HT-34 pp 1-11.

[18] Bennett D L, Davis M W and Hertzler B L 1980 Suppression of saturated nucleate boiling by forced convective flow *AIChE Symp.* 76 pp 91-103.

[19] Kubanek G R and Miletti D L 1979 Heat exchange and hydraulic characteristics of tubes with internal fins at Freon-22 movement under evaporation conditions *Proc. ASME Heat Trans.* (Moscow, Publishing house Mir) 4 pp 76-84.

[20] Antipin M K, Tarasevich S E and Yakovlev A B 1998 Flow regimes and hydraulic resistance of swirled air-water flow in short channel *Proc. of V Int. Sem. «Stability of flows of homogeneous and heterogeneous fluids»* (Novosibirsk: Institute of theoretical and applied mechanics SB RAS) pp 168-72.

[21] Shishkin A V, Tarasevich S E and Yakovlev A B 2017 Heat transfer at boiling of refrigerant R134aa in channels with inserts in the form of twisted tapes *Proc. Of Ann. Conf. of Nat. Com. Of RAS on heat- and mass trans.* «Fundamental and applied problems of heat and mass transfer» and XXI School-Sem. of young scientists and specialists under the guidance of Acad. of RAS Leont’yev A I «Problems of gas-dynamics and heat and mass transfer in power plants» (Saint-Petersburg: Publishing house MEI) 1 pp 398-401.

[22] Yagov V V 1995 Scientific heritage of D A Labuntsov and modern understanding of bubble boiling *Heat Trans.* 3 pp 2–10.