Critical heat flux density in diphasic thermosyphons

Konstantin O. Ponomarev[1,*], *Evgeniya* G. Orlova[1], and *Atlant* E. Nurpeiis[1]

[1]National Research Tomsk Polytechnic University, 634050 Tomsk, Russia

Abstract. The paper presents an analysis of known dependencies for determining the critical heat flux density in diphasic thermosyphons. The critical heat flux density for the created experimental model of thermosyphon were calculated on the basis of the theoretical contributions of 1) the occurrence of a “flooding” regime in a thermosyphon characterized by a disturbance of the hydrodynamic stability of the phase interface and the entrainment of the liquid phase by the gas flow; 2) the mutual influence of gravitational forces and surface tension; 3) S.S. Kutateladze hydrodynamic theory of the heat transfer crisis during boiling. It is found that the existing theoretical contributions which can be used to calculate the critical heat flux density and subsequently determine the minimum filling ratio of a thermosyphon are conditionally applicable.

1 Introduction

Accident-free operation of electronic, energy-generating devices is ensured by monitoring their temperature within the required limits designated by the manufacturer. Cooling of heat-loaded elements is possible with traditional systems using relatively large volumes of coolant, as well as systems based on diphasic thermosyphons – compact, resource-saving devices, capable of removing high local heat dissipations. It is known [1–5] that the efficiency of a thermosyphon is affected by the chemical composition of the coolant, filling ratio, geometric dimensions of a thermosyphon (height, internal cross-sectional area), inclination angle, material of construction, and the cooling conditions of the condensation zone.

When operating a thermosyphon, emergency operation modes may occur due to the heat and mass transfer crisis which is characterized by the absence of contact between the coolant and the surface of a thermosyphon evaporative part. The consequences of such an operation of a thermosyphon cooling system are overheating and ignition of a thermostabilized device or apparatus.

The known causes of the heat and mass transfer crisis [6–7] are breakdown of condensate from the thermosyphon walls, limiting steam content in the wall layer, formation of dry spots on the internal surface of the evaporator. Determination of the critical heat flux density $q_{cr}, kW/m^2$ at which the heat and mass transfer crisis occurs is necessary to calculate the minimum filling ratio of a thermosyphon with the coolant.

* Corresponding author: kop.tpu@gmail.com

The aim of this work is to determine the critical heat flux density for the created experimental thermosyphon model.

2 Determination of the critical heat flux density

Three parts are relatively distinguished in the thermosyphons [8–9]: evaporative, adiabatic (transport), and condensate (Fig. 1).

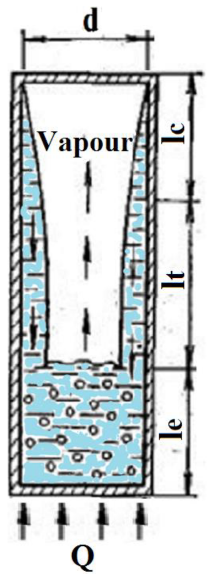

Fig. 1. Diphasic thermosyphon. l_e, l_t, l_c are lengths of evaporative, adiabatic (transport), and condensate parts, respectively; d diameter of a thermosyphon; Q heat flow.

The heat flow is removed from the heat-loaded element to the evaporative part of a thermosyphon filled with the coolant which heats up. The resulting vapor from the evaporative part moves into the adiabatic and condensation parts. Here the vapor condenses emitting the latent heat of the phase transition to the cooling medium. Condensate under the gravitational forces is transported to the evaporative part along the walls. The processes in a thermosyphon proceed continuously-cyclically which ensures heat transfer from the heat-loaded element to a thermosyphon.

A thermosyphon is a device with relatively small geometric dimensions. Therefore, at the ratio of the inner diameter d to the length of the evaporative part l_e $d/l_e < 0.2$ the boiling mechanism in it refers to the boiling in a small volume, if $d/l_e > 2$ the volume is considered as large [10].

In order to avoid a heat and mass transfer crisis in a thermosyphon, it is necessary to ensure its filling with a coolant in an amount greater than the minimum determined by the dependences [8, 11]:

$$\varepsilon_e = C_1 + \frac{0.8 \cdot l_c + l_t}{l_e} \cdot \frac{4}{d} \cdot \left(\frac{3 \cdot \mu_l \cdot l_e \cdot q_{cr}}{\rho_l^2 \cdot g \cdot r} \right)^{\frac{1}{3}} + \\ + \frac{\rho_v}{\rho_l} \cdot \left(\frac{l_c + l_t}{l_e} - \frac{0.8 \cdot l_c + l_t}{l_e} \cdot \frac{4}{d} \cdot \left(\frac{3 \cdot \mu_l \cdot l_e \cdot q_{cr}}{\rho_l^2 \cdot g \cdot r} \right)^{\frac{1}{3}} \right). \quad (1)$$

where l_e, l_t, l_c are lengths of evaporative, adiabatic (transport), and condensate parts, respectively, m; d internal diameter, m; μ_l dynamic viscosity of liquid, Pa·sec, q_{cr} heat flux density referred to the surface area of the heat supply, W/m^2; ρ_l liquid density, kg/m^3; ρ_v vapor density, kg/m^3; g acceleration of gravity, m/sec^2; r latent heat of vaporization, J/kg; C_1 coefficient which depends on the pressure of the coolant, the diameter of a thermosyphon, the thermo-physical properties of a liquid, and is taken from 0.2 to 0.33 [8].

$$\varepsilon_e = 1 - \frac{1}{1 + C_2 \cdot \left[\frac{q_{cr}^{\;2}}{2 \cdot \sigma \cdot \rho_v \cdot r^2} \cdot \left(\frac{3 \cdot q_{cr} \cdot \mu_l \cdot l_e}{\rho_l \cdot (\rho_l - \rho_v) \cdot g \cdot r} \right)^{\frac{1}{3}} \right]^{\frac{3}{4}}} \quad (2)$$

where σ is surface tension, N/m; C_2 coefficient dependent on the conditions of the surface heating and the thermo-physical properties of a liquid; for water is equal to 447 [11].

In formulas (1–2) the critical heat flux density q_{cr} is used. It depends on the thermo-physical properties of the liquid and the geometric parameters of a thermosyphon.

According to the analysis results of the known dependences, three groups of equations can be conventionally identified for determining q_{cr} [12–19] based on: 1) the theoretical contributions [12–15] of the occurrence of a "flooding" regime in a thermosyphon characterized by a disturbance of the hydrodynamic stability of the phase interface and the entrainment of the liquid phase by the gas flow. Regime takes place an intermediate position between the regions of a stable descending and stable ascending flow of a liquid film; 2) the mutual influence of gravitational forces and surface tension [16–18]; 3) S.S. Kutateladze hydrodynamic theory of the heat transfer crisis during boiling [19].

The first group includes the dependencies [12–15]:

$$q_I^{cr} = 0.25 \cdot \frac{r \cdot d^{1.5} \cdot \sqrt{g \rho_v \cdot (\rho_l - \rho_v)}}{l_e \cdot \left(1 + \sqrt[4]{\frac{\rho_v}{\rho_l}} \right)^2}, kW/m^2; \quad (3)$$

$$q_{II}^{cr} = 0.8 \cdot \left(\frac{d}{l_e} \right) \cdot r \cdot \sqrt{\rho_v} \cdot \sqrt[4]{\sigma \cdot g \cdot (\rho_l - \rho_v)}, kW/m^2; \quad (4)$$

$$q_{III}^{cr} = 0.526 \cdot \frac{r \cdot \sqrt{d} \cdot \sqrt{g \rho_v \cdot (\rho_l - \rho_v)}}{\left(1 + \sqrt[4]{\frac{\rho_p}{\rho_l}} \right)^2}, kW/m^2; \quad (5)$$

$$q_{IV}^{cr} = 3.2 \cdot r \cdot \left(th \cdot (0.5 \cdot \sqrt[4]{d} \cdot \sqrt[8]{\frac{g \cdot (\rho_l - \rho_v)}{\sigma}} \right)^2 \cdot \frac{\sqrt[4]{\sigma \cdot g \cdot (\rho_l - \rho_v)}}{\left(\frac{1}{\sqrt[4]{\rho_l}} - \frac{1}{\sqrt[4]{\rho_v}} \right)^2}, kW/m^2. \quad (6)$$

The second group includes [16-18]:

$$q_V^{cr} = 0.09 \cdot \left(\frac{d}{l_e} \right)^{0.9} \cdot \frac{r \cdot \sqrt{\rho_v} \cdot \sqrt[4]{\sigma \cdot g \cdot (\rho_l - \rho_v)} \cdot \sqrt{Bo}}{\left(1 + \sqrt[4]{\frac{\rho_v}{\rho_l}} \right)^2}, kW/m^2; \quad (7)$$

$$q_{VI}^{cr} = 0.1 \cdot \frac{r \cdot \sqrt{\rho_v} \cdot \sqrt[4]{\sigma \cdot g \cdot (\rho_l - \rho_v)}}{1 + 0.491 \cdot \left(\frac{l_e}{d}\right) \cdot \frac{1}{Bo^{0.3}}}, kW/m^2; \quad (8)$$

$$q_{VI}^{cr} = 0.8 \cdot \left(\frac{d}{l_e}\right) \cdot r \cdot \sqrt{\rho_v} \cdot \sqrt[4]{\sigma \cdot g \cdot (\rho_l - \rho_v)} \cdot \left(\frac{th\left(\frac{\sqrt[4]{Bo}}{2}\right)}{1 + \sqrt[4]{\frac{\rho_l}{\rho_v}}}\right)^2, kW/m^2; \quad (9)$$

where $Bo = d/\sqrt{\sigma/(g \cdot \rho_l - \rho_v)}$ is Bond number.

The third group includes [19]:

$$q_{cr} = K \cdot r \cdot \sqrt{\rho_v} \cdot \sqrt[4]{g \cdot \sigma \cdot (\rho_l - \rho_v)}, kW/m^2 \quad (10)$$

where K is stability criterion of a two-phase wall layer.

A stability criterion K in Eq. (10) depends on the thermo-physical properties of the heat-removing surface, the coolant and is in the range of $K = 0.09 \div 0.2$. The recommended values of K according to experimental data are $K = 0.16$ [20], $K = 0.12$ [21], $K = 0.13$ [22], $K = 0.14$ [23]. In [24–29], dependencies were obtained by definition of the stability criterion K.

In the present work calculations of the critical heat flux density for the created experimental thermosyphon model are performed. Table 1 shows the results obtained under conditions of filling thermosyphon with water at the following parameters: $d = 0.039\,m$; $l_e = 0.021\,m$; $\rho_l = 958.1\,kg/m^3$; $\rho_v = 0.597\,kg/m^3$; $g = 9.81\,m/\sec^2$; $r = 2260000\,J/kg$; $\sigma = 0.05904\,N/m$; $Bo = 15.56$; $\mu_l = 0.000279\,Pa \cdot \sec$.

Table 1. Critical heat flux density.

Dependences from references used on the basis of:	$q_{cr}, kW/m^2$
theoretical contributions of the occurrence of a “flooding” regime in a thermosyphon	
[12]	11571.9
[13]	12589.6
[14]	13110.1
[15]	11638.1
mutual influence of gravitational forces and surface tension	
[16]	3915.8
[17]	605.2
[18]	134.9
S.S. Kutateladze hydrodynamic theory of the heat transfer crisis during boiling	
[20]	1355.8
[21]	1016.9
[22]	1101.6
[23]	1186.3
[24]	1109.0
[25]	1264.0
[26]	1440.3
[27]	1207.8
[28]	1229.1
[29]	1105.3

Based on the analysis of the data presented in Table 2, it was found that the divergence between the values of the critical heat flux density obtained on the basis of: 1) the theoretical contributions of the occurrence of a “flooding” regime in the thermosyphon is 23.15%; 2) the mutual influence of gravitational forces and surface tension is 96.55%; 3) S.S. Kutateladze hydrodynamic theory of the heat transfer crisis during boiling is 29.4%.

In addition, using the dependencies on the basis of: 1) the theoretical contributions of the occurrence of a “flooding” regime in a thermosyphon the values of the critical heat flux density are an order of magnitude greater than the values obtained from the dependences on the basis of the mutual influence of the gravitational forces and S.S. Kutateladze hydrodynamic theory of the heat transfer crisis during boiling. It can be concluded that the existing theoretical contributions which can be used to calculate the critical heat flux density and subsequently determine the minimum filling ratio of the thermosyphon are conditionally applicable.

According to the results of the literature analysis [1–29] Russian scientific groups are found to apply Eq. (10) the most often, the foreign groups use the dependence of q_{cr} derived by Zuber N. [24] based on S.S. Kutateladze hydrodynamic theory of the heat transfer crisis during boiling.

3 Conclusions

There are a lot of researchers considering various aspects of the critical heat flux density and the list of authors presented in the paper is not exhaustive. It was found that many formulas based on the “flooding” and similarity theory are not suitable for determining the critical heat flux density during boiling of water in a diphasic thermosyphon with certain geometric parameters ($d = 0.039\ m$; $l_e = 0.021\ m$).

The divergence between the values of the critical heat flux density obtained on the basis of: 1) the theoretical contributions of the occurrence of a “flooding” regime in the thermosyphon is 23.15%; 2) the mutual influence of gravitational forces and surface tension is 96.55%; 3) S.S. Kutateladze hydrodynamic theory of the heat transfer crisis during boiling is 29.4%.

It can be concluded that at present the scientific basis for the design of energy-efficient, resource-saving cooling systems for heat-loaded elements based on thermosyphons is not developed at the level of prognostic modeling. To solve this scientific problem, it is necessary to conduct complex experimental studies of the heat and mass transfer, convection, boiling in thermosyphon using modern low-inertia, high-precision equipment for recording temperature, photo and video recording systems.

The reported research was supported by Russian Federation President Grant for state support of the Russian Federation leading scientific schools SS-7538.2016.8 (No 14.Y31.16.7538-SS).

References

1. A. Amiri, R. Sadri, M. Shanbedi, G. Ahmadi, B.T. Chew, S.N. Kazi, M. Dahari, Energy Convers. Manage. **92**, 322 (2015)
2. C.C. Chien, C.K. Kung, C.C. Chang, W.S. Lee, C.S. Jwo, S.L. Chen, Energy **36**, 415 (2015)
3. N.C. Chami, A. Zoughaib, Energy Build. **42**, 1267 (2010)
4. S. Jaisankar, T.K. Radhakrishnan, K.N. Sheeba, S. Suresh, Energy Convers. Manage. **50**, 2638 (2009)
5. H. Mirshahi, M. Rahimi, Iran J. Chem. Eng. **6**, 15 (2009)

6. M.K. Bezrodnyi, D.V. Alekseenko, Teplofizika Vysokikh Temperatur **15**, 370 (1977)
7. H. Imura, K. Sasaguchi, H. Kosai, S. Namata, Int. J. Heat Mass Transfer. **26**, 1181 (1983)
8. D.V. Feoktistov, E.A. Vympin, A.E. Nurpeiis, MATEC Web Conf. **72**, 01081 (2016)
9. K.O. Ponomarev, E.G. Orlova, A.E. Nurpeyis, MATEC Web Conf. **92**, 01006 (2017)
10. I.L. Pioro, Industrial Heat Engineering **7**, 24 (1985)
11. S. Rösler, M. Takuma, M. Groll, S. Maezawa, Heat Recov. Syst. CHP **7**, 319 (1987)
12. G. Wallis, *One-dimensional two-phase flows*, ed. by I.T. Alad'ev (Mir, Moscow, 1972) [in Russian]
13. O.L. Pushkina, Y.L. Sorokin, Heat Transfer Soviet Research **1**, 56 (1969)
14. R.S. Sakhuja, Mechanical Engineering **96**, 80 (1974)
15. C.L. Tien, K.S. Chung, Proc. 3rd Int. Heat Pipe Conf. 36 (1978)
16. C.L. Tien, K.S. Chung, AIAA J. **17**, 643 (1978)
17. Y. Katto, Trans. Japan. Soc. Mech. Engs. **44**, 3908 (1978)
18. M. Shiraishi, Prep. 6lh Int. Heat Pipe Conf. 609 (1987)
19. S.S. Kutateladze, *Fundamentals of the heat transfer theory* (Atomizdat, Moscow, 1979) [in Russian]
20. S.S. Kutateladze, Kotloturbostroenie **3**, 10 (1948)
21. E.A. Kazakova, Izvestiya AN SSSR. OTN **1**, 64 (1949)
22. Y.P. Chang, *An analysis of the critical conditions and burnout in boiling heat transfer* (USAEC Rep. TID-14004, Washington, DC., 1961)
23. O.N. Man'kovskij, A.R. Tolchinskij, M.V. Aleksandrov, *Heat exchange equipment for chemical production* (St. Petersburg, Himiya, 1976)
24. N. Zuber, Trans. Of ASME. J. Heat Transfer **80**, 711 (1958)
25. J.H. Lienhard, V.K. Dhir, J. Heat Transfer **95**, 152 (1973)
26. W. Bailey, E. Young, C. Beduz, Y. Yang, Thermal and Thermomechanical Phenomena in Electronics Systems, 2006. ITHERM'06. The Tenth Intersociety Conference on. – IEEE, 599 (2006)
27. V.M. Borishanskiy, Technical Physics. The Russian Journal of Applied Physics **26**, 452 (1956)
28. Y.P. Chang, N.W. Snyder, Chem. Eng. Prog. Symp. Ser. **56**, 25 (1960)
29. Y. Haramura, Y. Katto, Int. J. Heat Mass. Transfer. **26**, 389 (1983)