Flat-Plate Collector with Solar-Powered Pump and Problem of Boiling on Downward-Facing Surface

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Abstract. - Conceptual design of flat-plate collector (FPC) with integrated solar-powered pump (SPP) has been carried out. SPP represents simple heat engine - membrane pump operating through alternating of processes of evaporation and condensation in its working chamber. It should provide circulation of water using part of absorbed by FPC heat returning it finally to the same heat carrier. Two basic versions of structural layout of FPC have been considered: the first - with flow-through absorber (with circulation of water through riser pipes welded to absorbing plate) and the second – with absorber with gravity-assisted heat pipes (GAHPs). Important role of proper organization of boiling heat transfer on downward-facing heating surface of working chamber, in terms of efficient operation of SPP, is stated. Thermo-hydrodynamic peculiarities of this process are considered. The ways of improvement of reliability and efficiency of SPP are outlined.

Key Words – Flat-Plate Collector, Solar-Powered Pump, Boiling, Downward-Facing Surface, Multifactoring

1. Introduction

Flat plate collector (FPC) presents the most engineered commercially efficient device among appliances utilizing solar energy [1-7]. Nevertheless, further improvement of technical and economical characteristics of FPC remains as a quite topical problem.

Among potential lines of development it presents certain interest creation of FPC providing circulation of heat carrier (as a rule, water) through heat supply system without consumption of electricity. This problem may solved through inclusion into FPC of solar-powered pump (SPP) [8-9] representing simple heat engine - membrane pump capable to operate using part of FPC as a heat source and circulated water as a cooling agent.

Another potentially valuable aspect of inclusion of SPP into FPC is linked to peculiarities of metering characteristic and startup and stop of SPP.

In particular, SPP self-starts with overcoming by temperature of heat source of certain threshold value and, vice-versa, stops operation with reduction of the same temperature below roughly the same value. Besides, water delivery by SPP depends on temperature of heat source. Capability of SPP to self-start with heating of FPC, to regulate water flow rate with FPC capacity and to stop operation with cooling of FPC potentially can be used through self-control of the heat supply system.

At the same time pumping process turns out to be dependent on efficient organization of boiling heat transfer in working chamber of SPP. In particular, efficiency of SPP increases with reduction of duration of the stage of evaporation of intermediate working agent. In this context related problem of boiling on downward-facing heating surface in specific conditions of SPP needs to be studied in more details.

The paper presents results of conceptual design of FPC with integrated SPP. Certain preliminary analysis of the ways of realization of the conceptual design also is presented. In terms of efficient operation the role of proper organization of boiling heat transfer on downward-facing heating surface of working chamber of SPP also is considered.

Schematic design of two basic versions of FPC with integral SPP is carried out for solar heat absorber of typical sizes (2.0 m X 1.0 m). The values of maximum heat capacity of FPC equal to 1200 W (600 W/m^2) and maximum water flow rate through FPC equal to 100 kg/h (50 $kg \cdot h^{-1} \cdot m^{-2}$) are accepted.

It also is assumed that, to a certain extent, temperature of the part of the absorber supplying by heat SPP is higher than temperature of the main part of the same absorber (because of specific conditions of heat transfer through SPP) and its maximum may exceed 100 ^oC.

Taking in account real and potential characteristics of SPP, it also was accepted that heat consumption on water pumping process makes around 10% of heat capacity of

FPC. By this purpose a tenth of the absorber is thermally separated from the main part. Below this part is called as a "pumping-powering part" (PPP). It also is assumed that temperature lag at SPP results certain additional superheating of PPP as compared to the main part of the absorber. By the way, the heat extracted for operation of SPP finally is returned by the same heat carrier into heat supply scheme of FPC.

The paper also considers aforementioned related problem of boiling heat transfer on downward-facing heating surface in specific geometrical and thermo-hydrodynamic conditions of working chamber of SPP.

Further, let's start with brief description of SPP and current status of its development.

1. Solar-powered pump

SPP represents a classical membrane pump supplemented by a chamber consisting evaporator in the form of downward-facing capillary surface heated by external low-temperature source of energy (e.g., by the heat extracted from FPC) and condenser in the form of elastic membrane cooled from the reverse side by circulated water [8-9].

The chamber is fed by certain charge of intermediate low-boiling working agent undergoing successive processes of boiling (or evaporation) and condensation. The schematic of SPP is presented in Fig. 1.

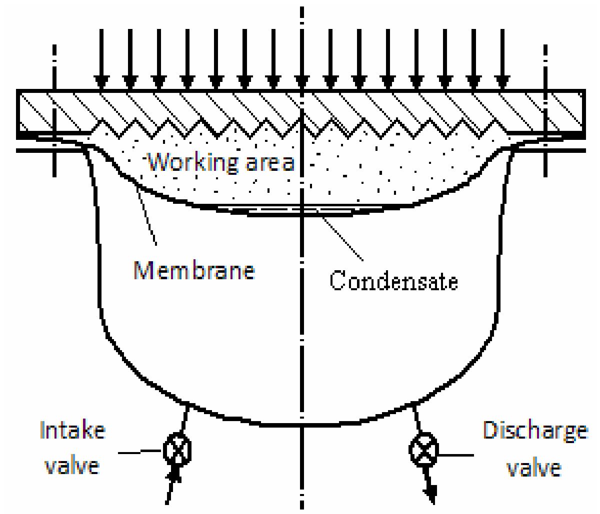

Fig. 1. Schematic of SPP

While standing the membrane bears against wetted by working agent capillary structure. When heating is started, nucleation of vapor phase of working agent starts only consequent to certain superheat of capillary surface against saturation temperature.

Further, in the wake of nucleation, two stages of phase conversion take place: the first – initial nucleate boiling of working agent in the capillary structure – and the second – pure evaporation form the same structure - consequent to reduction of heating surface superheating at the first stage.

Finally working agent evaporates quite rapidly displacing the membrane and delivering water through discharge valve.

Displacement of the membrane stops when the charge of the working agent is completely evaporated and the capillary structure is dried-up. Correspondingly it re-starts the process of superheating of the evaporation surface.

Simultaneously condensation of working agent continues on inner surface of the membrane. Vapor pressure reduces in the working area and the membrane begins reverse motion to the evaporation surface. Thereby a charge of water is sucked through the intake valve.

To the end of reverse motion the membrane brings the charge of working agent to newly superheated capillary structure and next working cycle starts.

Concurrent performance by the membrane of the functions of water discharge and suction element, condensation surface and the tool returning condensed intermediate agent to capillary heating surface allows to realize full thermodynamic cycle of the steam engine within only one working area. It mades it possible to form extremely simple (may be, the most simple among the familiar steam engines) heat engine - pump with corresponding lowering of production cost.

At the same time realization of full cycle within only one working area also leads to certain disadvantage of the steam engine: during the starting stage of the cycle condensation coincides with evaporation and the part of vapor crosses working area without accomplishment of useful work. In this connection some measures should be taken to minimize negative consequences of this parasitic flow.

Simplified analysis of thermodynamic cycle of SPP is presented in [8]. Through certain idealization (e.g., ignoring of vapor superheating near heating surface when it is dried or fluid phase subcooling in condensed film) the thermodynamic cycle of SPP is considered as sum of isochoric compression with heat input, isobaric-isothermal expansion with heat input, isochoric compression with heat output and isobaric-isothermal compression with heat output.

In connection with aforementioned parasitic vapor cross-flow the thermodynamic cycle completely is located in the wet vapor area and vapor dryness fraction to the end of isobaric-isothermal expansion is the parameter controlling corresponding reduction of the cycle efficiency. Finally, the following equation is derived for efficiency of the thermodynamic cycle SPP:

$$\eta = \frac{x_{max}(\upsilon_g - \upsilon)\Delta P}{\Delta h} \qquad (1)$$

where x_{max} is maximum vapor dryness fraction during the cycle (to the end of isobaric-isothermal expansion); υ_g is specific volume of vapor at maximum saturation pressure of the working agent; υ is specific volume of liquid phase of the working agent at the same saturation pressure; ΔP is difference between maximum and minimum values of saturation pressure of the working agent during the cycle; Δh is difference between maximum and minimum values of enthalpy of the working agent during the cycle

Simplified thermodynamic cycle of SPP is presented in Fig. 2.

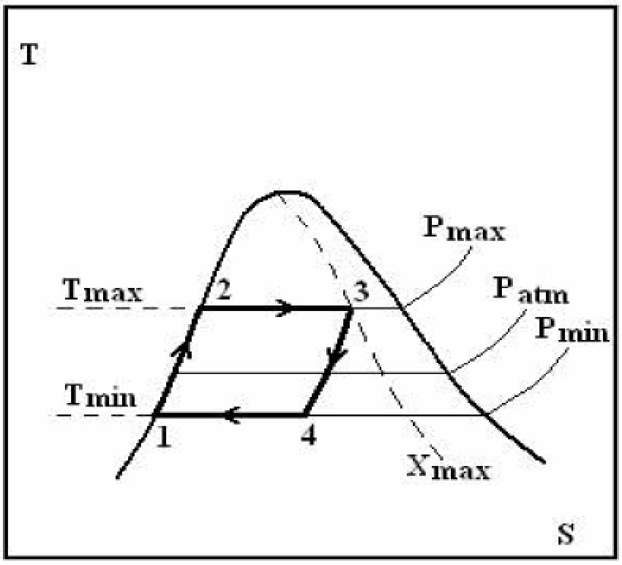

Fig. 2. Simplified thermodynamic cycle of SPP (T – temperature; S - entropy; P - pressure)

Comparison of achievable levels of efficiency of SPP, according equation (1), with efficiency of Carnot cycle is presented in Fig. 3. Calculations are made for methanol as a working agent, for minimum saturation pressure (suction pressure) equal to 0.7 bar and for maximum vapor dryness fraction 0.8. It also is supposed that temperature drop between maximum and minimum saturation pressures 20 - 60 ℃ presents realistic working range for SPP using FPC as a heat source and circulated water as a cooling agent. By the way, corresponding net pressure head of SPP changes in the range 0.9 – 5.0. bar.

As it follows from the comparison, potential efficiency of SPP is quite moderate. However, this circumstance fully can be compensated by potential cheapness of SSP and by capability of SSP to utilize low-potential heat sources. It becomes important improvement of design of SPP though its further engineering. It also remains topical search for more efficient working agents.

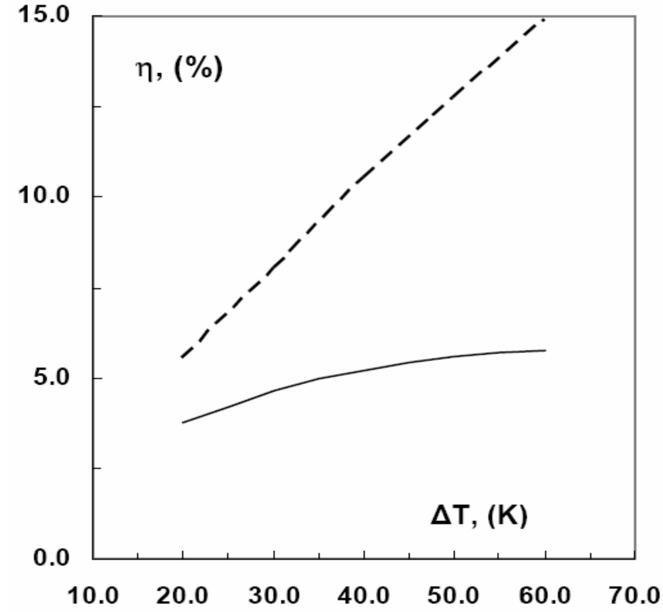

Fig. 3. Comparison of the theoretically achievable levels of efficiency of SPP (continuous curve) with efficiency of Carnot Cycle (broken curve)

As it follows from the equation (1), minimization of aforementioned reduction of the cycle efficiency by parasitic vapor cross-flow is possible through elevation of x_{max}. Dependence of efficiency of SPP on maximum vapor dryness fraction is presented in Fig. 4.

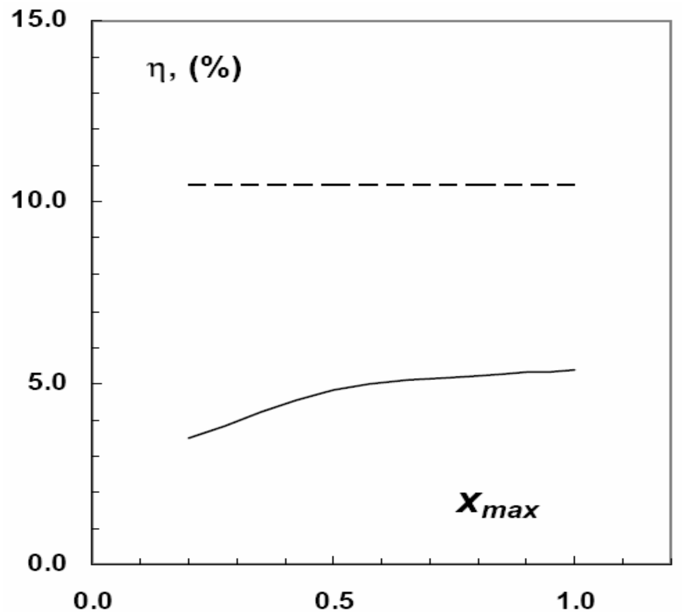

Fig. 4. Dependence of efficiency of SPP on maximum vapor dryness fraction (continuous curve) and efficiency of Carnot Cycle (broken line)

Calculations are made for methanol as a working agent, for minimum saturation pressure equal to 0.7 bar and for temperature drop between maximum and minimum saturation pressures 40 ℃.

As it follows from Fig. 4, increase of x_{max} noticeably elevates efficiency of SPP, especially, in the range of low values of dryness fraction. Realization of this potential is possible through reduction of the ratio of intensity of evaporation to condensation intensity during isobaric-isothermal expansion (through shortening of duration of full evaporation of working agent). In this context it gains importance the related problem of enhancement of boiling and evaporation heat transfer on downward-facing heating surface in specific conditions of SPP.

During past years three experimental prototypes of SPP were manufactured and experimentally investigated. The prototype 1 has allowed demonstration of feasibility of SPP. The prototypes 2 and 3 have allowed demonstration of reasonable level of efficiency of pumping process and operability of SPP in terms of its self-start. Efficiency of prototypes 2 and 3 is reflected by Fig. 5. Presented experimental curves cover the ranges of the capacity of heating of the evaporator of SPP in the range 30-80 W and water delivery in the range 10-50 kg/h. Methanol was used as a working agent in all experimental prototypes.

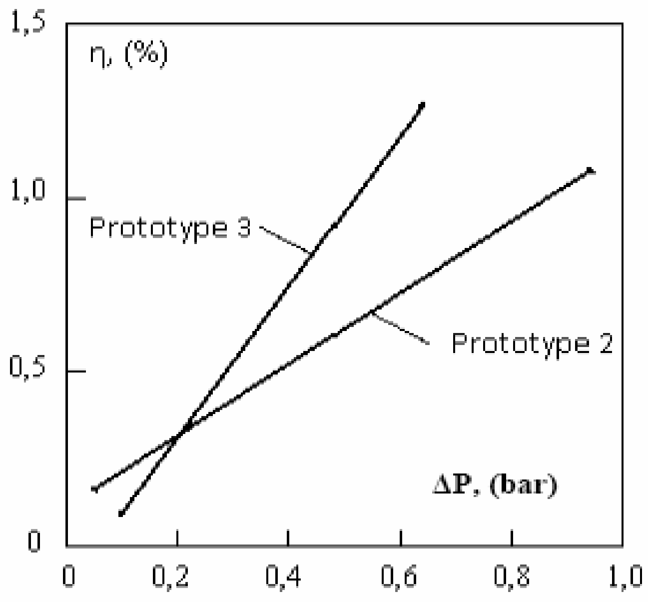

Fig. 5. Efficiency of experimental prototypes 2 and 3 versus net pressure head of SPP

As it follows from Fig. 5., really achieved levels of efficiency of SPP is noticeably lower than the same levels predicted by simplified theory. Such a result evidently reflects existence of certain potential of improvement of efficiency of SPP,

As it was mentioned above, it presents special interest possibility of using of SPP through control of operation of FPC based at self-start and self-stopping characteristics of SPP and dependence of water circulation rate on intensity of heating of SPP as well.

Self-start of SPP takes place only consequent to certain superheat of capillary surface of the evaporator against saturation temperature. By its part, concrete value of the superheat depends on sizes of vapor (or gaseous) nucleus remained between the capillary surface and the membrane bearing this surface.

Provided moderate preliminary degassing of the working agent and the working area surfaces, necessary for nucleation superheat of the heating surface easily may be brought up to 10 ^oC.

If geometrics and thermal parameters of the heating surface and the charge of the working agent are properly set up, a superheat around 10 ^oC turns out to be quite enough for full evaporation of this charge through the first cycle of SPP operation.

As regards to further operation of SPP, it has no linkage to nucleation because the heating surface always meets returned by the membrane charge of working agent in superheated (dried-up) condition.

In such a manner, SPP self-starts consequent to overcoming by temperature of heating surface of the threshold value determined by following relation:

$$T_{ss}=T_s+\Delta T, \quad (2)$$

where T_{ss} is temperature of self-start of SPP; T_s is saturation temperature of working agent at the opening pressure of discharge valve (maximum saturation pressure during the cycle); ΔT is superheat of the order 10 ^oC.

Required value of T_{ss} (for instance, in the range 70-90 ^oC) can be set up through choice of intermediate working agent with suitable saturation parameters taking also in account concrete thermal and hydraulic parameters of heat supply system.

As regards to self-stopping of SPP, it takes place when temperature of the heating surface reduces below T_s (for instance, through reduction of heat capacity of FPC towards evening) Besides, standing SPP is impermeable for heat carrier.

In such a manner, self-start and self-stopping characteristics of SPWP fully correspond to operation regime of FPC. In this context, it seems reasonable to explore practical aspects of using SPP through control of launch and stopping of heat supply system.

As regards to using of SPP through control of water circulation rate through FPC, for now only principal possibility of such a control can be pointed out. Final conclusions should be based on detailed study of metering characteristics of SPP.

2. Conceptual design of FPC

With the purpose of creation of autonomous solar collector operating without consumption of electricity two basic versions of structural layout of a new type FPC with integrated SPP are considered.

The first version of FPC (Fig. 6) presents combination of SPP with classical absorber provided by lower header (LH), upper header (UH) and riser pipes.

A lower tenth of the absorber is thermally separated from the main part and serves as a pumping-powering part (PPP) supplying SPP by heat. SPP provides circulation of water. Further the heat is transferred through the membrane to heat carrier concurrently serving as cooling agent of SPP. In such a way heat extracted by PPP returns into basic heat supply system.

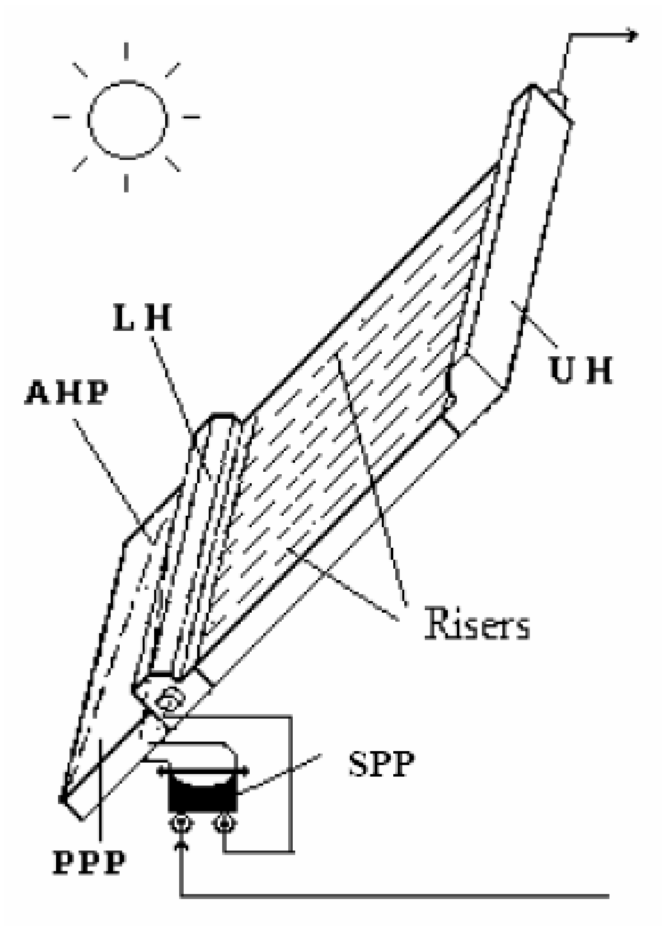

Fig. 6. FPC with classical absorber and SPP.

Gathering of energy from all surface of PPP and further transportation to the evaporator of SPP is provided by <-shaped auxiliary heat pipe (AHP) capable to operate as wickless gravity-assisted heat pipe (GAHP). Besides, the upper end of AHP is linked to the evaporator of SPP and the latter holds lower position in the heat supply system.

SPP itself is arranged at the entry of cool heat carrier into FPC. As a result, heat carrier with minimum temperature firstly removes heat from the membrane of SPP providing condensation of working agent, further heats up in the main part of the absorber and is delivered to consumer.

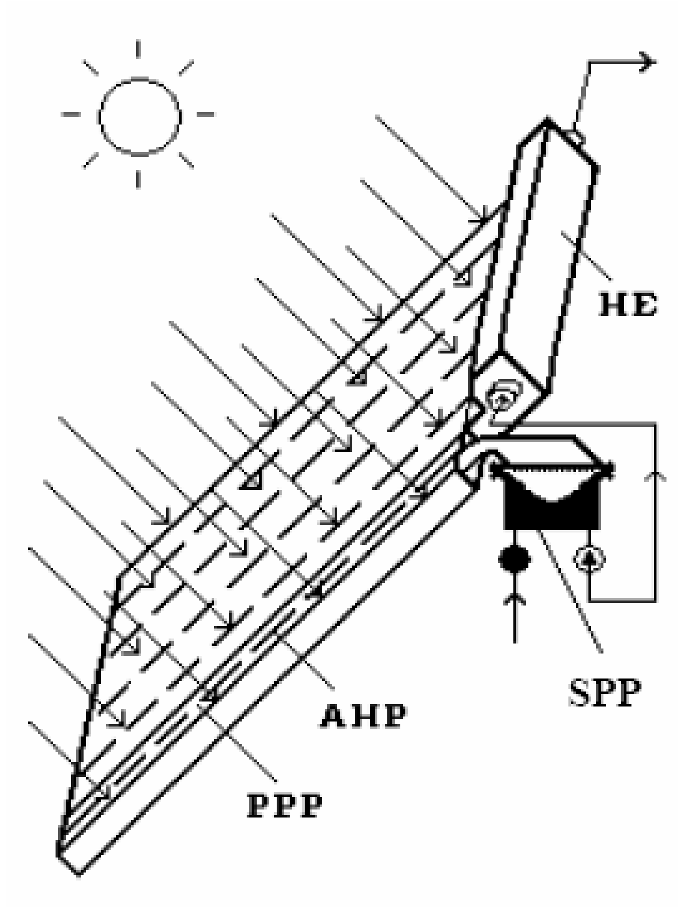

Fig. 7. FPC with GAHPs and SPP

The second version of FPC (Fig. 7) presents combination of SPP with the absorber provided by GAHPs (instead riser pipes) and by upper heat exchanger (HE) (condensation section) transferring gathered by GAHPs heat to circulated water.

Outer GSHP and corresponding strip of the absorber (near outer longitudinal strip) are used as PPP. This GAHP is linked to the evaporator of SPP by its upper end and thereby is used as AHP.

Longitudinal assembling of GAHPs with the absorber and upper position of the condensation section allows arrangement of SPP to upper edge of the absorber preserving thereby its lower position in the heat supply system. Otherwise, schematic and operational peculiarities of the second version of the FPC with integrated SPP are the same as in the case of the first version of the FPC.

3. Boiling on downward-facing surface

As it was mentioned above, enhancement of heat transfer at the stage of phase conversion of working agent on heating surface during isobaric-isothermal expansion gains significance in the context of improvement of efficiency of SPP.

The process of phase conversion includes two main stages: the first – initial boiling in narrow gap between the capillary structure of downward-facing heating surface and the membrane bearing this surface, and the second – evaporation form wetted capillary structure. Besides, these stages are quite differing in the context of acting heat transfer mechanisms.

At the past stage of investigation our efforts mainly have been focused on investigation of boiling heat transfer on downward-facing heating surface.

As it follows from existing investigations of boiling on inclined and downward-facing surfaces [10-13], corresponding heat transfer processes possess specific peculiarities. For instance, it gains the form of so-called “bubble ballet” pumping effect of growing bubble (PEGB) under certain conditions of boiling of subcooled liquid on downward-facing surface that can result specific heat transfer regularities [14]. Simultaneously it undergoes certain transformation conditions of microlayer evaporation (MLE) on downward-facing surface,

Another important peculiarity of the process is linked to possibility of occurrence of so-called duration-dependent multifactoring of boiling heat transfer on downward-facing heating surface [15].

According to [16], during developed boiling, HTC depends only on two "external" factors - heat flux and effective radius. As it follows from corresponding analysis, such a conservatism of developed boiling heat transfer can be linked to following three basic conditions:

- Triggering of short-run actions of cooling mechanisms by bubble growth onset at nucleation site;
- Existence of great (practically unlimited) number of stable nucleation sites with roughly uniform effective radii irrespective are they operating or potential;
- Prevailing contribution of heat removal by liquid phase convection.

According to multifactoring concept [16], a failure to meet any these conditions results essential transformation of heat transfer regularities. At that, depending on concrete conditions, the circle of influencing HTC factors may be widened by parameters of inter-phase hydrodynamics, intensity of body force, contact angle, subcooling, sizes, form, orientation and thermal characteristics of heating surface, distribution of nucleation sites, and prehistory of the process. Besides, in [16], there are distinguished two main types of multifactoring:

- The first – connected with onset of dependence of effective radius on a degree of penetration of liquid into nucleation site (wetting-dependent multifactoring),
- The second – connected with transition to prolonged duration or uninterrupted regime of action of any intensive cooling mechanism (duration-dependent multifactoring).

Wetting-dependent multifactoring occurs at the condition $\beta/2 > \theta$ (β is cone angle of conical recess of heating surface serving as a nucleation site; θ is wetting angle) when effective radius of nucleation site stops to be a constant equal to the radius of the mouth of the recess.

Immediate transition to wetting-dependent multifactoring may be observed only in rare cases of boiling system with reducing in time contact angle. In the majority of cases developed boiling and wetting-dependent multifactorous boiling of the same liquid may be observed only in separate systems.

Duration-dependent multifactoring quite often may origin consequent to developed boiling, for instance, through transition to prolonged or even uninterrupted action of PEGB or MLE with structural transformation of two-phase flow. Similar transition also may take place with change of intensity of body force or with variation of inclination angle of heating surface in the gravity field.

From the view of structural transformation of two-phase flow boiling in minichannels and microchannels also is considered as potential sphere of strong manifestation of duration-dependent multifactoring [17].

Effects potentially linked to duration-dependent multifactoring especially manifest itself through specific character of boiling heat transfer curves, generation of strong reverse vapor follows, related cyclical oscillations and flow instabilities observed in minichannels and microchannels [18-22]. The more so as the nature of observed in microsystems thermo-hydrodynamic feedback effects still remains to be identified [21].

In contrast to wetting-dependent multifactoring, establishment of conditions of transition to duration-dependent multifactoring is much more complex problem. Clarification of regularities of such a transition requires consideration of structural development of corresponding two-phase flows that represents independent multifaceted problem.

At the same time, duration-dependent multifactoring results transition to heat transfer regularities corresponding to so-called model of the theatre of actors [17]. Thereby, in connection with diversity of cooling mechanisms, the problem of theoretical assessment of HTC becomes extremely complex. It requires comprehensive multifactorous numerical modeling of all details and stages of operation of different cooling mechanisms (similar to an attempt made in [23] for the case of subcooled flow boiling).

As regards to boiling on downward-facing heating surface, among all processes potentially connected with multifactoring, it should be considered as the most suitable process for validity check of multifactoring concept.

Downward orientation of heating surface hinders the process of departure of vapor bubbles causing prolongation of immediate contact of the bubbles with heating surface. Besides, the effect is much more significant during boiling of subcooled liquid drastically restricting the growth of vapor bubbles and increasing delay of the bubbles on heating surface.

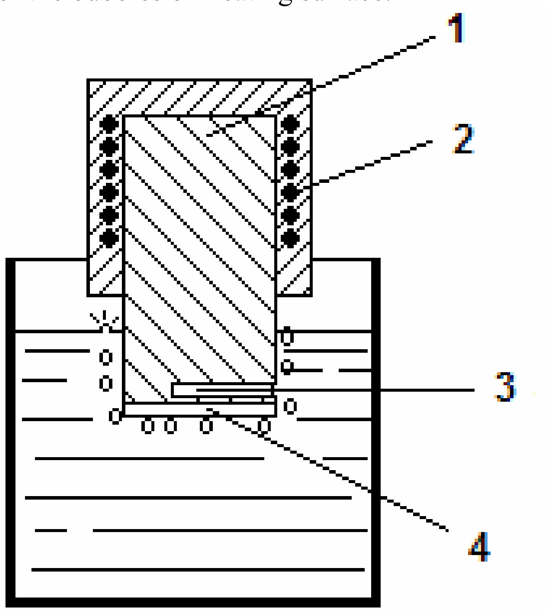

Fig. 8. Schematic of experimental set-up for investigation of boiling heat transfer on downward-facing disc: 1 – cooper cylinder; 2 – electric heater; 3 – thermocouple; 4 – heated disc.

Correspondingly, it significantly increases duration of action of such intensive cooling mechanisms as MLE and PEGB. At the same time, in the processes with prevailing role of cooling effects pointwisely distributed on heating surface, HTC becomes dependent on capability of heating surface to redistribute heat in transverse direction.

By the goal of investigation of multifactoring during boiling of on downward-facing heating surface experimental set-up was created a schematic of which is presented in Fig. 8.

Process of nucleate boiling has been realized on a disc 4 at two versions of orientation in gravity field (upward-facing and downward-facing). The results of the both of series of experiments are presented in Figures. 9 and 10. Experiments have covered boiling of saturated and subcooled liquid.

Standard procedures were used of measurement of thermal parameters and determination of heat flux (q) and heat transfer coefficient (HTC) (α). Heating capacity was determined through parameters of electric heater 2 taking in account heat losses.

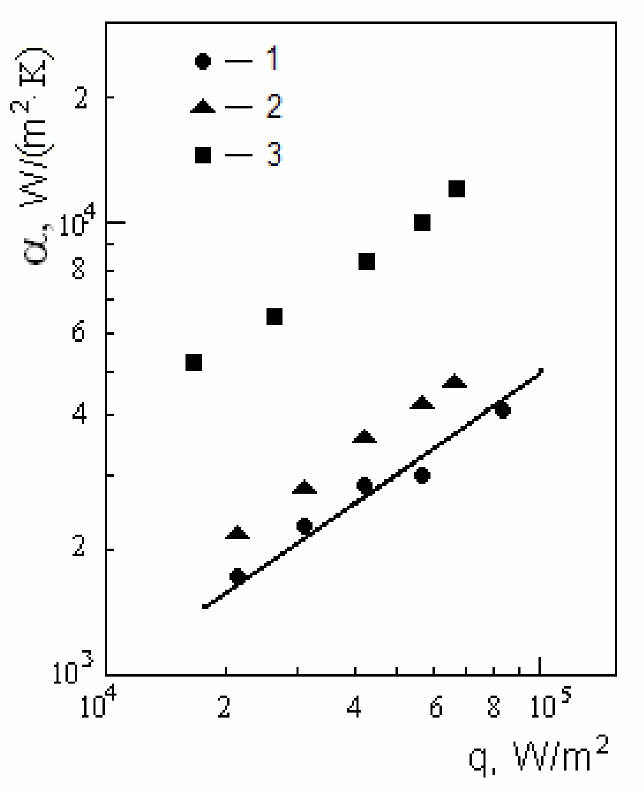

Fig. 9. Experimental data on boiling heat transfer of benzol on upward-facing and downward-facing end face of the cooper cylinder: 1 – boiling of saturated liquid on upward-facing surface; 2 – boiling of saturated liquid on downward-facing surface; 3 – boiling of subcooled liquid on downward-facing surface; solid line – developed boiling heat transfer law according [16].

Two series of experiments were performed: the first through boiling on the end face of cooper cylinder 1 and the second on the disc 4 with soldered to the end face of the cooper cylinder 1. Accuracy of determination of HTC is evaluated as ∓20%.

Experiments have been carried out through boiling of benzol at atmospheric pressure. Boiling of subcooled liquid was performed at subcooling around 10 ℃.

Analyzing presented experimental data, in the first place, attention should be drawn to the data received on upward-facing surfaces (points 1 in both of series). As it follows form presented data, heat transfer on upward-facing surface fully corresponds to developed boiling heat transfer law [16] (solid lines in both of series), irrespective to drastic difference between thermal characteristics of boiling surfaces.

Similar correspondence also reflects the fact that used boiling surfaces were nearly identical to commercial surfaces with average effective radius of nucleation sites roughly equal to 5 μm.

It should be mentioned also that in the same conditions it has been established experimentally independence of HTC, determined based at superheat of boiling surface relative to saturation temperature, on liquid subcooling (corresponding experimental points are not presented in Figures 9 and 10).

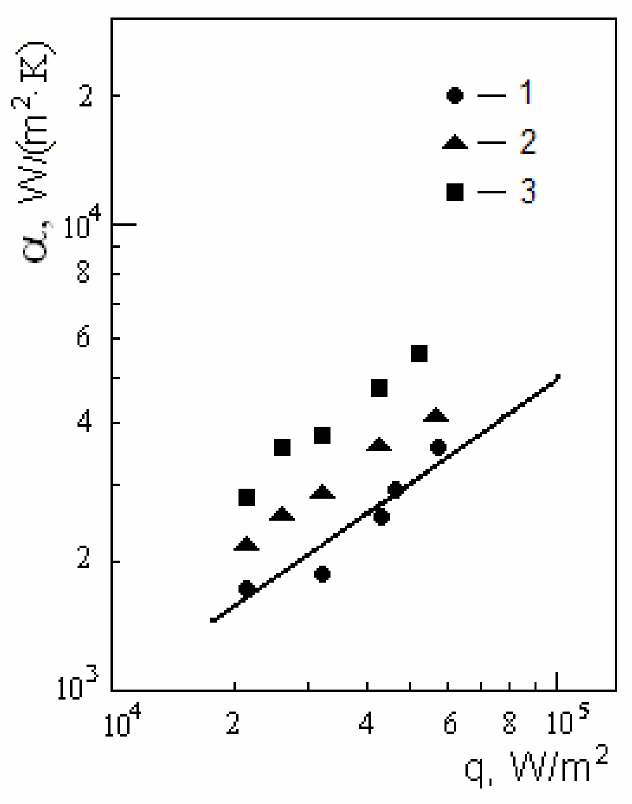

Fig. 10. Experimental data on boiling heat transfer of benzol on upward-facing and downward-facing disc made from stainless steel: 1 – boiling of saturated liquid on upward-facing disc; 2 – boiling of saturated liquid on downward-facing disc; 3 – boiling of subcooled liquid on downward-facing disc; solid line – developed boiling heat transfer law according [16].

The second part of the experiments includes regimes of boiling of saturated liquid on downward-facing surfaces (points 2 in both of series).

As it follows from presented data, boiling of saturated liquid on downward-facing surface is characterized by more high HTCs although increase of this parameter relative to developed boiling only slightly exceeds accuracy of its determination.

Effect of heat transfer enhancement is much more significant in third part of experiments including regimes of boiling of subcooled liquid (points 3 in both of series). Besides, the effect drastically depends on thermal characteristics of boiling surface achieving the factor 3-4 in the case of cooper surface (Fig. 9).

Reveled in the experiments peculiarities of boiling heat transfer may be linked to multifactoring phenomenon. Downward orientation of boiling surface hinders the process of departure of vapor bubbles causing prolongation of immediate contact of the bubbles with heating surface.

Correspondingly, it significantly increases the role of microlayer evaporation. Finally, it occurs duration-dependent multifactoring involving additional factors influencing HTC. Besides, the effect is much more significant during boiling of subcooled liquid drastically restricting the growth of vapor bubbles.

At the same time, in the processes with prevailing role of microlayers pointwisely distributed on heating surface HTC is linked to capability of heating surface to redistribute heat in transverse direction [24-26].

In such a manner, downward orientation of boiling surface may lead to significant enhancement of boiling heat transfer, especially, if the surface is made from material of high thermal conductivity.

4. Conclusion

Efficient realization of the conceptual design needs solution of a number of problems, including further design study of SPP by the goal of improvement of its efficiency and reliability. A part of problems is linked to operability assurance of combined system FPC-SPP.

Through development of pre-production prototype of SPP, together with detailed study of self-control and metering characteristics and enhancement of related heat transfer and thermodynamic processes, certain set of other problems remains to be solved. The problems of upsizing of SPP and selection of proper high-reliability material for the elastic membrane seem as comparatively weighty.. Design study of the versions of assembling of SPP with FPC also is necessary.

Detailed study of self-control and metering characteristics of SPP and further investigation and enhancement of heat transfer and thermodynamic processes taking place in SPP also are necessary.

In particular, further intensification of evaporation from capillary surface of the evaporator and condensation on the membrane can contribute to improvement of efficiency and capacity of SPP. Besides, it may turn out to be useful some means and approaches developed in the field of heat pipes [24].

In the context of operability assurance of combined system FPC-SPP the main problem is achievement of efficient heat supply of SPP by AHP. From the view of cost-efficiency of the heat supply system, solution of this problem through utilization of wickless GAHPs seems as more attractive.

In the context of feasibility of the last solution the second version of FPC with GAHPs and integrated SPP (Fig. 6) looks less problematic. In this case AHP (in the form of the outer GAHP separated from other similar GAHPs) preserves practically the same basic regime of operation.

As regards to FPC with classical absorber and integrated SPP (Fig. 5), according preliminary evaluations, achievement of reliable operability of AHP in the form of <-shaped wickless GAHP through required maximum heat capacity (around 120 W) also represents solvable technical problem.

Some peculiarities of operation of AHP are linked to counter-current two-phase circulation in the zone of return bend of AHP potentially presenting the factor restricting heat capacity of such a GAHP. This aspect of operation of <-shaped wickless GAHP requires special investigation. .

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