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Thermal Stress State of the Surface During Heating Due to Drop Condensation

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Initially, steam condensation takes place in the form of individual drops in condensation centers on the solid surface, known as drop condensation, or in the form of a liquid film on the solid surface - known as film condensation. In the vast majority of cases, the heat transfer processes associated with this phenomenon are the subject of research. The work is devoted to the thermal stress state analysis of a solid body heated by steam condensation, on the surface of which drops have formed at the initial stage of heating. This process is accompanied by an increase in thermal stress, which in the case of drop condensation, reaches a local maximum at the drop boundary and can be characterized by the stress concentration factor used by the authors in analogy with the thermal or mechanical concentration factor in solid mechanics.

Keywords: stress concentration factor, drop, thermal stress, drop condensation, film condensation.

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Introduction

The initial stage of power units startup is preliminary heating of steam pipelines between a boiler and a steam turbine, whose duration could reach 20–25% of the total startup duration. The shortest heating mode of thick-wall steam pipelines is their heating through the steam condensation on their internal surface, because the heat transfer coefficients during heat exchange through condensation (is over $5000\,\mathrm{W/(m^2{\cdot}K)}$), which is far higher than during heat exchange through convection. The heat exchange process during condensation of water steam on the internal surface of heated pipelines was many times described in the literature [1]. The heat exchange mechanisms during dropwise and film condensation of water steam are known, each of them features a specific level of thermal stresses occurring in the heated wall, which is specific only to that mechanism. The problems of calculation of thermal stressed state during convective heat exchange are well studied, however, thermal stressed state of parts of equipment when heated by dropwise condensation is poorly studied today. The authors tried to assess the level of stresses occurring within a flat wall when heated by dropwise condensation, when the drop shape specifics cause formation of non-uniform field of temperature stresses in it. Its characteristic is the stress concentration factor, whose value depends on the shape and size of drops, their number, mutual disposition and the time of existence. The longer the duration of a drop existence, the higher the value of the stress concentration factor.

1. The stress concentration factor during condensation as further evolution of the terms of thermal and mechanical stress concentration factor

In solid body mechanics the stress concentration occurs in presence of heterogeneities in the geometry or material of a structural element, which cause interruption of the stress flow. These can be such elements as holes, grooves, notches, fillets. The stress concentration can also occur as a result of incidental damages, e.g. dents and scratches.

The tensile stress concentration can be expressed through a dimensionless concentration factor K_t, which refers to the relationship between the highest stress and the nominal one, which, e.g. for round hole in a semi-infinite plate reaches 3.0 [2].

For ductile materials, high loads could cause a localized plastic yield, which usually occurs first in case of the stress concentration, meanwhile brittle materials are generally being destructed under the stress concentration. However, iterative (cyclic) loads of even a low level could cause formation of fatigue cracks leading to destruction even of ductile materials. When heating a solid body through steam condensation by the dropwise condensation mechanism, the occurring stresses can also be described by the coefficient similar to the structural coefficient of the stress concentration that reaches the highest value at the drop boundary, which is explained by step-like decrease of stresses at the transition to an unloaded surface of the solid body. Which is it caused by? The drop by its weight causes elastic strain of horizontal surface, on which is was formed, by displacing the surface material along the drop perimeter, tending to preserve its volume equal to the initial one. Change of the surface position in space, where the drop was formed, decreases the value of that coefficient.

2. Physical setup of the study problem. Description of the calculation model

In applied problems of heating thick-wall steam pipelines of power units the main thing is to define its duration, which depends on thermal stresses occurring in them and a permissible number of the heating–cooling down cycles. In the earlier experimental studies of power plants startup modes units with supercritical pressure and the power of 300 MW TPP with intermediate steam reheating it was postulated that preliminary heating of high-pressure steam pipelines and hot legs of steam pipelines of intermediate steam reheating should be performed by organizing the steam flow through these steam pipelines in case of convective heat exchange mechanism [3,4].

While high-pressure steam pipelines are heated relatively fast along the whole length because of opening the large cross-section steam bypasses, organizing convective heating of hot legs of steam pipelines after intermediate steam reheating in the conditions of single bypass thermal schemes appeared to be quite difficult problem due to the absence of possibility of consuming large quantities of steam, a high demand of metal and impossibility of heating by convection of the end segments upstream of a intermediate pressure cylinder of a steam turbine, the length of which intermediate some cases exceeded 10 m. The complex situation is during heating of high-pressure steam bypass pipes between stop and control valves of K-300-240 steam turbines as well, the length of the pipes also exceeds 10 m, and the drains is at their middle part; so the vertical segment of the pipe 168×32 mm from the drain to the body of the turbine control valve with the length over 8 m is heated in the non-flow mode.

Calculations of thermal stressed state of these steam pipelines during their preliminary convection heating (before steam supply to the turbine) have shown that their heating rates, permissible in terms of the low cycle thermal fatigue, are $0.5-1.5^\circ$C/min. Similar calculations performed for CCPP high-pressure and intermediate pressure steam pipelines and steam reheaters outlet headers of heat recovery steam generators enabled justification of their heating rates having close values.

The paper [1,5,6] directly referred to the preference of heating through steam condensation, however, there is a series of constraints in application thereof, including due to unfavorable arrangement and insufficient flow capacity of the drains systems that fail to provide efficient condensate removal during heating of steam pipelines by steam condensation. In fact, drain pipelines generally had a great hydraulic resistance due to their small diameter $d_n = 20-30$ mm and big length exceeding 10 m in presence of local resistances, such as bends and shutoff valves. With that heating method there is a risk of discharge of residues of not removed condensate into the flow part of the turbine.

Based on the foregoing and subject to the fact that heating technology through steam condensation is simpler and more efficient, in this study we performed the analysis of specifics of the physical mechanism of such heating and the justification of its applicability in practice in terms of thermal strength of the heated parts of power equipment. To resolve the problem set, it is necessary to consider various condensation mechanisms.

While the studies of heat transfer processes during dropwise and film condensation are being paid a significant attention, the studies devoted to the analysis of thermal stresses occurring in a heated part during steam condensation on its surface, as well as to the analysis of the stress concentration during heating by condensation are extremely rare. The study [7] deals with the problem of heat transfer through the condensate film during steam pipelines heating at the initial stages of startup, and pipe metals „cooling“ taking place at the same time and, as a consequence, thermal stresses with variable sign occur. It should be noted that heating of cooled down steam pipelines during cold and warm startups (the steam pipelines metal temperature does not exceed 100°C) begins with formation of condensate drops on the internal surfaces of the steam path elements, such as headers, steam pipelines, internal surfaces of the bodies of stop valves, in flow part of turbines in contact with the steam, whose existence duration is low.

The most common mechanism of drops formation is that these appear in certain locations of nucleation (pits, grooves, roughness), wherein the region between the drops is inactive in relation with the condensation [7,8]. The drops are growing up first through the steam condensation on their surface, and then by coalescences, while the surface area between growing drops remains virtually dry. It is the mechanism, which was taken as the basis in the estimation analysis of its impact on thermal stressed state of the heat exchange surface. The absence of stresses within the heated surface at the initial stages of its heating is also in favor of that approach [7].

The dropwise condensation features a high intensity of heat exchange ($15-20$ times higher, than in case of film condensation) [9]. The dropwise condensation process relates to initial stage of heating, this is why stationary steam condensation is under review. In the space between drops the heat from steam is transferred by thermal conductivity [9]. In the process of heating by condensation, small drops of condensate increase in size, coalescence with formation of a film, thus reducing temperature stresses within the heated wall [8].

Single drops of different sizes formed on the surface of flat infinite plate with the thickness of 34 mm, made of steel 12CrMV (which is typical for the walls of outlet headers of high-pressure steam superheaters) are considered as a first approximation. The model represents a ball segment, whose height is lower than the drop diameter. The contact angle

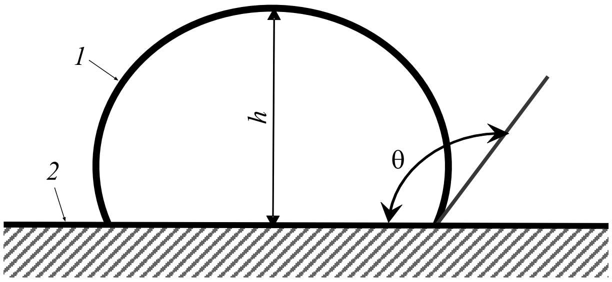

Figure 1. Schematic image of steam condensate drop (*1*) with the angle of wetting θ to the plate (*2*) (h — is the maximum drop height).

of wetting θ (Fig. 1), i.e. the angle formed by a tangent to the surface of condensate–steam phases separation and by a hard surface, with the apex at the point of drop contact with the surface, and always measured towards the inside of the liquid phase $> 90^\circ$, which is an attribute of its non-wettability [9].

The finite element method calculation was performed by means of ANSYS software complex having a wide range of tools to resolve the problems of heat exchange and solid body strain mechanics.

For the purpose of analysis of thermal stressed state of the plate in case of dropwise condensation we considered various calculation models with single drops with the diameters of 1, 2.5 and 5 mm on its surface (Fig. 2, *a*), groups of 9×5 drops of the same size with the distance from each other equal to their diameters (Fig. 2, *b*), a group of drops with the diameter of 5 mm in contact with each other (Fig. 2, *c*), which corresponds to their state prior to coalescences and formation of a liquid film. The adopted number of drops in the group is associated with simplification of calculations and was determined by the capabilities of the used computer.

The conditions of absence of motions in the perpendicular direction to the planes of side faces of the plate and to the symmetry plane were preset. Drop-free surfaces of the plate and planes obtained as a result of the structure section by the symmetry plane are thermally insulated. The third nature contact conditions were applied to the heat exchange surfaces of the drops (the coefficient of heat transfer from steam to drop surface is taken equal to 10 000 W/($\mathrm{m}^2\cdot$K) [9], the temperature is equal to the saturation temperature at the current steam pressure). The plate surface between drops is heated through the heat conductivity [1].

The calculations took into account that the heat transfer takes place only through the drops and is constrained by their thermal resistance, which rises as far as the drop sizes increase.

The steam temperature near to the drop surface and near to the heat exchange surface is equal to the saturation temperature; the temperature below the drop near to the plate surface is a bit lower (not more than by 0.5°C).

In addition, the case was considered, when the whole water volume concentrated in drops with the diameter of 5 mm is uniformly distributed over the plate surface forming a film with the thickness of 0.1–0.15 mm (the thickness was defined for a plate of certain size used in simulation calculations).

Herein we did not take into account the plate heating with the drop size increase [1,8] from the minimum to the preset one, and the initial plate temperature in all calculations was taken equal to 50°C, which for sure provides its heating through condensation.

3. Analysis of calculation results

The distribution of temperatures obtained from the calculation in the cross-section of the plate is given in Fig. 3: for individual drops with the diameter of 5 mm of the system of drops with the distance from each other equal to the drop diameter and in contact with each other prior to their coalescences forming a film.

The stresses distribution is of the same nature as for the temperatures. The maximum values of stress intensity obtained according to the temperature values given above (Fig. 3), 10 s after the heating start for a single drop were 80.7 MPa, for the drops with the distance of 5 mm from each other were 80.9 MPa; the minimum ones — for a single drop — 80.1 MPa, for the drops with the distance of 5 mm from each other: 79.2 MPa; for the drops in contact with each other, the maximum stress intensity values are observed 3.0 s after the heating start and are 103 MPa, the minimum ones — 98.6 MPa.

The stresses in the plate under the condensate film, whose thickness was defined based on its volume forming the drops, are equal to zero.

The stress concentration factors both for single drops of various diameters and for a group of drops were defined based on the results obtained. The concentration factor was defined as a relationship between the maximum values of stresses within the plate at the drops locations and the nominal values of stresses, which refer to the stresses that occur in a drop-free part of the plate at a distance from them, which is determined in accordance with the St. Venant's principle.

The concentration factor change was considered from the heating start until the film formation.

The time of transition from one drop size to another (Table 1) was calculated based on the drops size growth rate.

The drops growth rate was determined by using the formula for a hemispherical drop [8,9]:

$$\frac{dR}{d\tau} = 2\frac{\lambda_{liq}\vartheta_{drop}}{r\rho_{liq}R},$$

where R — is the curvature radius of the drop surface having the shape of spherical segment, [m], τ — is the time, [s], λ_{liq} — is the thermal conductivity coefficient of

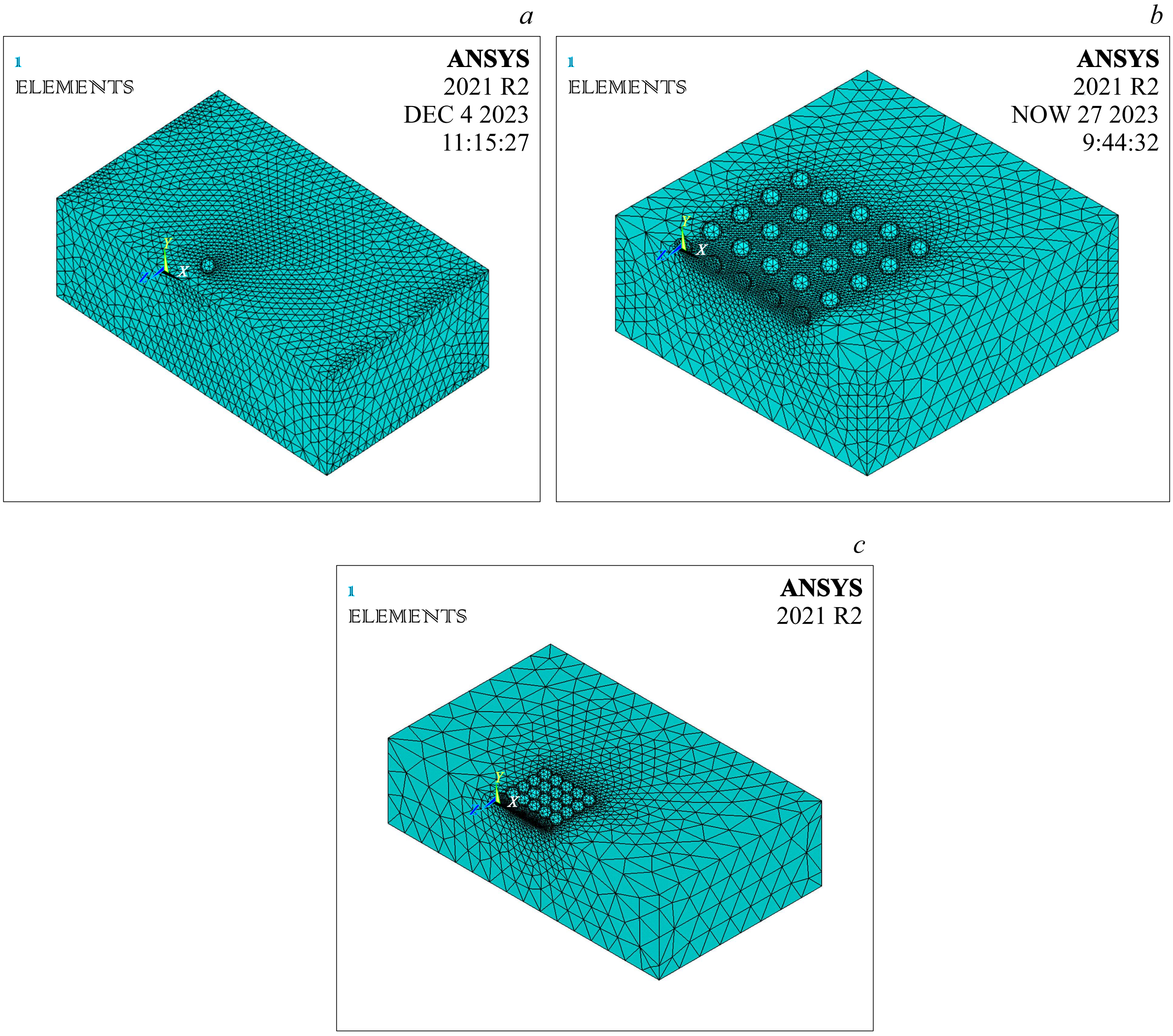

Figure 2. Finite element models of the drop condensation on the surface of a flat plate with the drops having diameter of 5 mm: *a* — single drop; *b* — a group of 9×5 drops with the diameter of 5 mm, with the distance of 5 mm from each other; *c* — a group of 9×5 drops contacting each other prior to coalescences.

Table 1. Calculation of the drops existence time

Calculation by using the formula (1)			Note
R (Radius of the drop), m	$dR/d\tau$, m/s	τ, s	
$0.5 \cdot 10^{-3}$	$1.8 \cdot 10^{-4}$	4.16	Drop growth from the radius of 0.5 mm to the radius of 1.25 mm
$1.25 \cdot 10^{-3}$	$7.21 \cdot 10^{-5}$	10.4	Drop growth from the radius of 1.25 mm to the radius of 2.5 mm
$2.5 \cdot 10^{-3}$	$3.61 \cdot 10^{-5}$	2.77	Drop growth from the radius of 2.5 mm to the radius of 2.6 mm

liquid, [W(m·K)], $\vartheta(\xi, \varphi)$, ϑ_{drop} — is the drop temperature as the function of polar radius ξ and polar angle φ, is the temperature head $\vartheta_{drop} = T_{surf} - T_{wall}$, [°C], T_{surf} — is the temperature of temperature drop external surface of the condensate drop equal to the saturation temperature at given steam pressure, [°C], $T_{surf} = 250°\mathrm{C}$, T_{wall} — is the wall temperature, [°C], $T_{wall} = 50°\mathrm{C}$, r — is the specific heat of phase transition, [J/kg], ρ_{liq} — is the evaporation unit density, [kg/m^3].

The concentration factor calculation results for a single drop and the drops forming a group are given in Table 2 and in Fig. 4.

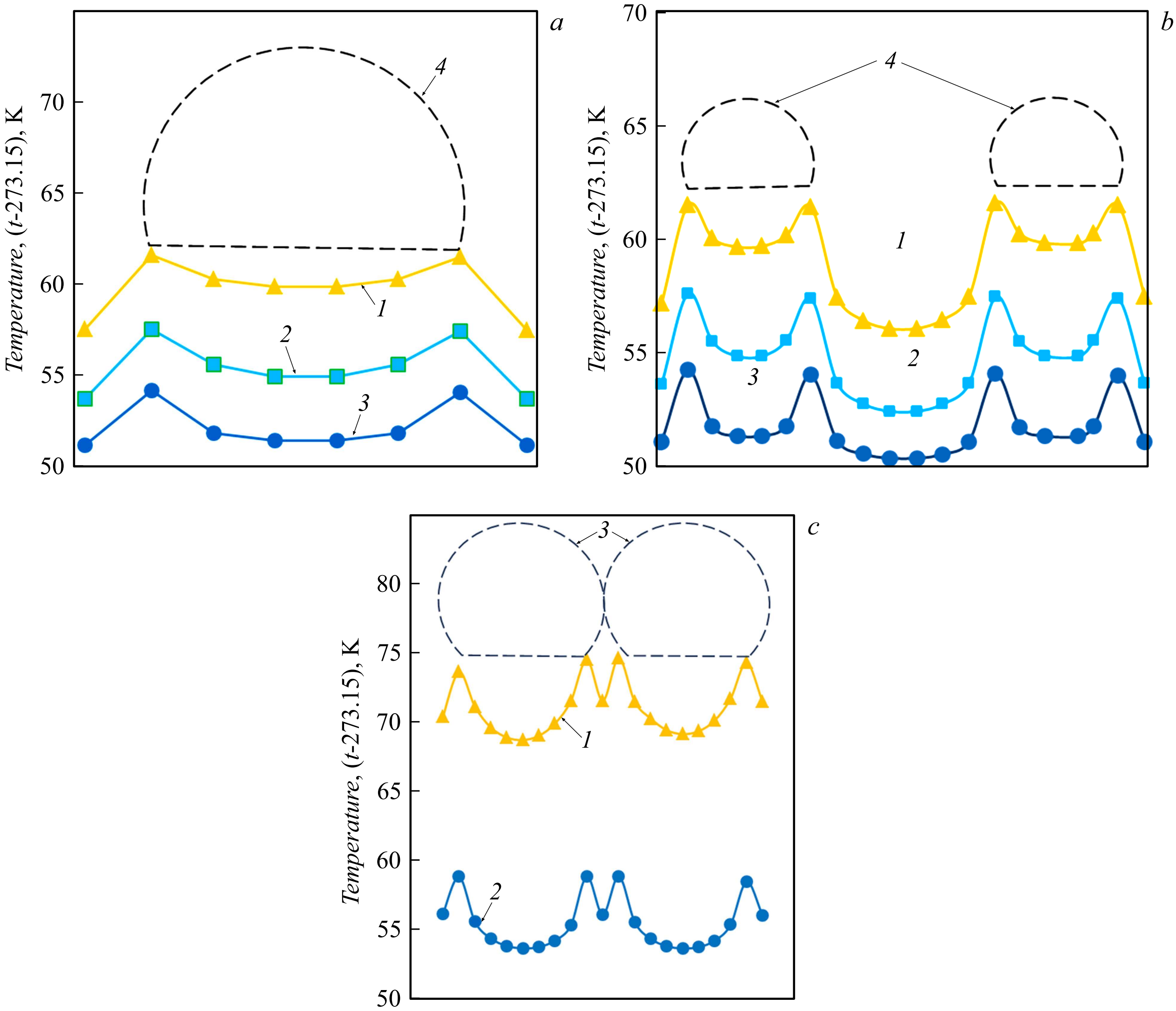

Figure 3. Distribution of temperatures in the plate under the drops with the diameter of 5 mm: *a* — single drop; *b* — a group of 9 × 5 drops with the diameter of 5 mm with the distance from each other of 5 mm; *c* — a group of 9 × 5 drops in contact with each other prior to coalescences. *1* — the temperature 10 s after the heating start, *2* — the temperature 3 s after the heating start (for the drops in contact with each other *1*), *3* — the temperature 0.5 s after the heating start (for the drops in contact with each other *2*), *4* — drops (for the drops in contact with each other *3*).

Table 2. The stress concentration factor values during heating by condensation for a single drop and for a group of drops

Drop diameter, mm	Stress concentration factor during heating by condensation	
	Single drop	Group of drops
1	1.14	1.2
2.5	1.18	1.4
5	1.31	1.84

Figure shows time dependence of the stress concentration factor value at the location of condensate drops contact with plate during heating by dropwise condensation.

Load on the plate from the system of drops causes its elastic strain making a fringe pattern of the stresses distribution by the surface. This is why the total level of stresses in the system of drops (Fig. 4, *a*) interferogram rises relative to a single drop (Fig. 4, *b*).

Therefore, thermal stresses at the boundary of drops during heating of the substrate have

$$\sigma_t = K_t \sigma,$$

where K_t — is the stress concentration factor at the boundary of the drops contact with the substrate. The stress concentration factor shall take into account the superficial tension coefficient characterizing the work of molecular forces in case of change of the free surface area.

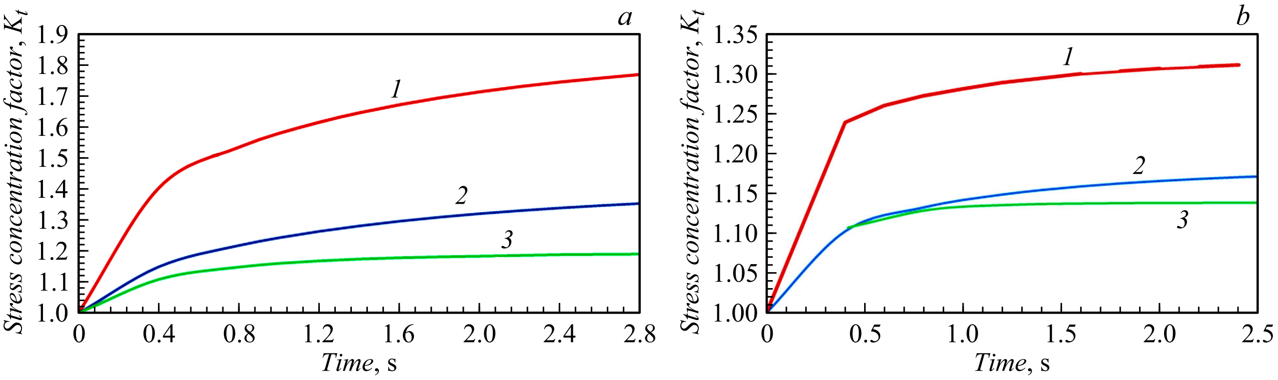

Figure 4. The stress concentration factor change in time during the dropwise condensation with the drops of different diameter: *a* — for a group of drops, *b* — for single drops. *1* — the drops with the diameter of 5 mm in contact with each other prior to their coalescences, *2* — the drops with the diameter of 2.5 mm, *3* — the drops with the diameter of 1 mm.

For the case of heating by dropwise condensation in question the relationship for the concentration factor K_t can be represented as

$$K_t = 1 + 2q\sqrt{\sin(\pi - \theta)},$$

where θ — is the angle of wetting (Fig. 1), q — the coefficient of material sensitivity to the concentration of stresses changes within the interval 0.6–0.9 [10].

According to the performed calculations of the thermal stressed state of a high-pressure header wall 426 × 34 mm with the condensate film on it, even during its heating at a step-like increase of the steam pressure, the maximum stresses on the internal wall surface do not exceed 85 MPa, and at the pressure increase rate of 1 MPa/min — 45 MPa [7]. The maximum value of stresses occurring in the plate with the thickness of 34 mm with drops on it in contact with each other, having the diameter of 5 mm, prior to coalescences is 103 MPa. In case if the drops are at a distance from each other approximately equal to their diameter, the stress in the plate does not exceed 80 MPa.

Therefore, one can say that the stresses occurring in the metal in case of dropwise and film condensation are comparable in terms of the value, moreover, in certain conditions the stresses during dropwise condensation may exceed the stresses occurring in case of film condensation.

However, the film condensation is determinant in the analysis of thermal stressed state of the wall during its heating by condensation. Such conclusion results from a small duration of the drops existence until their coalescences and the film formation. At that the stresses do not reach the maximum values, which is contributed by inclined or vertical position of the heat exchange surface (e.g., a steam pipeline or a header).

As it was said above, application of the heating by steam condensation technology requires organization of efficient drain systems, by means of which it would be possible to completely remove condensate formed during heating. However, thermal schemes at a TPP equipment operated at the present time often are insufficiently effective, steam pipelines have blind segments with a large length, condensate removal from them is complicated. In these cases one can use an engineering solution, according to which the steam pressure in steam pipelines should be decreased for a short time by 5–10% from the current value, which allows to evaporate the whole residual condensate and to remove the steam generated [11]. For example, when heating by steam with the pressure of 3–3.5 MPa the pressure decrease by 0.3 MPa at the final stage of heating leads to boiling up and evaporation of condensate in case of the saturation temperature decrease by 5–6°C [12].

Conclusion

The study deals with the stressed state of a plate heated by steam condensation on its surface. It is shown that thermal stresses in the heated plate depending on the condensation mechanism are distributed non-uniformly over its surface, under drops, in spaces between them and under the film. As a result of calculations performed numerical values were obtained for concentration of stresses occurring during heating, which refer to the relationship between the maximum stresses in the plate under drops or film and the nominal stresses, which occur on the drop-free surface. Stresses in the plate occurring during heating by dropwise condensation depend on the drop size, its existence time, and the number of drops formed. The longer the existence time of individual drops, the higher their number and size, then the higher the level of stresses occurring at their location. Asymptotic value of the concentration factor for the drops when these get in contact prior to coalescences reaches ≥ 1.8.

In case of film condensation the value of stresses occurring in the heated plate depends on the saturation temperature change rate. In all cases the steam pipelines heating through condensation duration is significantly lower (by more than 3 times) than in case of convective heating. The stresses occurring in metal in case of dropwise and film condensation are comparable and relatively low (about

100 MPa). However, due to a small duration of existence of the drops prior to their coalescences and film formation, the film condensation is determinant in the analysis of the thermal stressed state of the wall.

The steam pipelines heating reliability could be significantly increased through decrease of the steam pressure in steam pipelines by a small value (about 5–10%) at the final stage of such heating, thus completely evaporating the condensate residues generated during heating and not removed through the drain system.

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Conflict of interest

The authors declare that they have no conflict of interest.

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