The Problem of Geothermal Fluid Use in Power Engineering

Povarov O.A.

Moscow Power Engineering Institute 14, Krasnokazarmennaya St., Moscow, 111250, Russia

Keywords: Multi-component flow, mass transfer, erosion-corrosion, dissolution, deposits, experimental research, physicochemical model, principles of criterion modeling, stress corrosion cracking

ABSTRACT

The report gives results of long-term fundamental researches of geothermal fluid, hydro-gas-dynamics problems and erosion-corrosion effect of multi-component environments upon metals. Results of experimental researches of crisis phenomena in upper border curve zone, dispersed structure of two-phase flows, processes of liquid skins formation and flow and moisture separation, of physical-chemical erosion-corrosion processes and corrosive metal cracking under tension.

1. INTRODUCTION

Long-term fundamental researches of Russian scientists and specialists from leading institutes and enterprises became the basis for creation of national geothermal energy engineering industry and construction of series of geothermal electrical and heat plants.

Pollution and humidity of geothermal fluid coming from wells exceeds many times the indices of fresh steam at traditional power plants, Povarov O.A. and Tomarov G.V. (1997). So special steam preparation program (SPP) is necessary providing its necessary quality at GeoPP turbines inlet.

Erosion-corrosion of metals and formation of deposits in GeoPP equipment depend to a great extent on local physical-chemical parameters and chemical composition of liquid phase (skin) that are determined first of all by inter-phase gas and admixtures distribution, phase transformation processes and mechanical phase separation, Povarov O.A. (1988). Data available today for values of balanced coefficients of inter-phase substances distribution (Cb) concern the zone of pressures exceeding GeoPP working range (see fig. 1,a) Povarov O.A. and Tomarov G.V. (1997).

Researches on location implemented at Mutnovsky reservoir permitted discovering principally important effect consisting in deflecting of Cb values for some corrosion-active substances from “classical” lines of radial diagram (see fig. 1,b), Povarov K.O. (2000) which is the new approach towards estimation of liquid phase corrosion properties.

This phenomenon is based upon physical and chemical processes of interaction of various substances as well as influence of inter-phase thermodynamic non-equilibrium.

2. CRISIS PHENOMENA IN THE ZONE OF TOP BORDER CURVE

Detailed researches of steam condition during transition from superheated zone into humid one showed there are thermodynamic and gas-dynamic crisis phenomena.

During research of gas-dynamic characteristics of nozzle lattice during steam transition through saturation state with formation of fine-dyspersated moisture it was discovered that biggest losses of steam kinetic energy ξ_{st}, changes of flow rate coefficients μ and flow outlet angles α_1 are observed close to saturation line x = 1. Experiments, Filippov G.A. et al. (1981), with turbine stage also showed presence of crisis phenomena in the zone of steam phase transition.

Instability of gas-dynamic characteristics is interconnected with pulsating characteristics of flow that also undergo abrupt changes in phase transition zone, Povarov O.A. (1984). Investigation of average deceleration pressure $\bar{p}_0$ pulsation amplitude at inlet edge of nozzle blade installed after preswitched-on stage showed that pulsation amplitude depends essentially on steam parameters (fig. 2). During inleakage of superheated steam ($\Delta t_o > 0$) upon blade average pressure pulsation amplitude increases but with passing across saturation line pressure pulsations begin to decrease abruptly; this is connected with appearance of fine-dyspersated moisture in edge tracks of working grate rotating before investigated stage.

Intensive changes of pulsations of static and full pressures stated during transition across saturation state lead to pulsations of thermodynamic temperatures and deceleration temperatures (fig. 2). In regime range with initial superheating $\Delta t_o < 2 \div 7$ K the wall is in undercooled state when its temperature is lower than saturation temperature. Maximal undercooling of wall ΔT_w is approximately 12 K and can be observed during regimes with initial humidity before stage $y_o = 0,3 \div 0,4\%$. With increase of initial humidity undercooling decreases, and in the area $y_o = 1,5 \div 1,7\%$ wall temperature becomes equal to local saturation temperature. Similar changes are undergone by complete deceleration temperature measured before nozzle grate, Deych M.Ye. et al. (1990).

Passing across saturation line x = 1 is accompanied by efficiency decrease in the area of minor superheating ($\Delta t_o \leq$ 20K) and then its increase up to humidity values y < 2%. With appearance of steam in undercooling stage decrease of available energy takes place and as a consequence efficiency decrease at the area $\Delta t_o > 0$. Formation of moisture in investigated stage leads to decrease of superheating and losses connected with it, but this process is accompanied also by irreversible losses due to phase transitions and further efficiency decrease. Appearance of moisture at inlet into investigated stage leads to more balanced passing of steam condensation processes and efficiency increase.

Analysis of presented data shows that in turbine flow part extremum of thermodynamic and gas-dynamic parameters is noted during transition of steam from superheated into humid state near upper border curve x = 1. During moisture appearance parameters instability decreases, and during steam humidity $y > 1{,}5 \div 2\%$ it is practically not expressed.

3. LIQUID SKINS FORMATION AND FLOW PROCESSES

Fine-dyspersated moisture forming in the process of steam expansion during passing across saturation line x = 1 is precipitated, and at turbine stage blades and discs liquid skins appear. Process of liquid skins formation and flow directly depends upon structure of border layer, humid steam floe regimes in channel, state of surface, chemical composition of environment and some other factors; this is confirmed by researches implemented at MPII experimental turbines.

First data on thickness of liquid skins on turbine stage blades were acquired by Povarov O.A. et al. (1984) at experimental turbine ET-12 in MPEI. Liquid skins thickness measurement results at nozzle and working blades for various initial steam parameters before investigated stage showed that at small initial humidity (y<1%) stable liquid skins are already present at blades, and with increase of steam humidity from 0 to 1,5% the liquid skin thickness increases both on nozzle and on working blades. These experiments also discovered presence of unstable liquid skin for steam parameters $\Delta t_o < 10K$ before grate that is the evidence of existence of solutions with increased contents of corrosion-aggressive admixtures near saturation line.

Formation of liquid skin flows to a great extent depends on angle of flow inleakage upon blades, Martynova O.I. et al. (1998). Fig. 3 shows the values of liquid skins thickness for various angles of flow inleakage upon nozzle grate ($\alpha_o=64^o$, 89^o и 116^o) where it seen well that change of flow inleakage angle leads to essential redistribution of skin thickness. This becomes especially apparent at blade back in root and peripheral profiles. For example, for inleakage angle $\alpha_o=64^o$ at back at blade root profile the skins are not detected at all but for leakage angle $\alpha_o=89^o$ at inlet blade area (sensor No 1) moisture was already observed and for angle $\alpha_o=116^o$ stable skin with thickness of 50-55 mcm (sensors No 1 and 2) was detected. The same trend was tracked also at blade peripheral profile (sensors No 6,7,8) but at this profile δ_{sk} reaches more essential values (up to 150 mcm).

It was stated that two-phase flow pulsations and fluid quality affect essentially the precipitation of fine-dyspersated moisture and formation of liquid skin currents in turbine stage channels.

4. DISPERSED STRUCTURE OF TWO-PHASE FLOWS

Research of dispersed structure of humid steam flows in turbine machines flow parts is one of most present-day and hardly realizable tasks. For measuring size of moisture drops formed in the process of steam expansion in turbine, and of humidity extent of steam, special measurement systems were developed and created in MPEI, Povarov O.A. et al. (2000), Semenov V.N. et al. (1999), that allow investigating fraction composition of humid steam flows in real time scale both at experimental and on-site turbines. Measurement elements of these systems are optical probes based upon light diffusion method.

Experimental researches implemented at experimental and on-site turbines using optical probes, Povarov O.A. et al. (1998) showed that size of condensate initial drops formed during steam expansion with passing across saturation line, lie in range $r_d = 0{,}05\text{-}2{,}0$ mcm.

Fig. 4 shows results of experiments on measuring moisture particles size and steam humidity after first stage of experimental turbine ET-3M. Values of humidity y and drop radius r_d after three profiles by blade height were acquired at constant regime parameters (p_o, T_o, $p_к$, G, n = const). Scatter in values $r_к$ and y is connected with the fact that diagrams show data of a series of experiments implemented at various water-chemical regimes and various initial concentrations of admixtures in steam before turbine.

In medium profile by blade height the drop size is $r_d = 0{,}07 \div 0{,}1$ mcm at humidity $y = 0{,}8 \div 1{,}3\%$. In peripheral profile drop size and humidity are lower ($r_d = 0{,}06 \div 0{,}08$ mcm, $y = 0{,}5 \div 0{,}9\%$). Maximal values of moisture particles size are noted between root and medium profiles ($r_d = 0{,}09 \div 0{,}12$ mcm, $y = 0{,}9 \div 1{,}2\%$).

Acquired experimental data are well correlated with the data of two-dimensional calculation of steam current in turbine flow part (fig. 4a).

5. PHYSICAL AND CHEMICAL EROSION-CORROSION PROCESSES

One of main reasons of emergency situations and failures of GeoPP equipment are erosion-corrosion metal damage. Basing upon implemented complex of experimental and theoretical researches scientific bases were developed, main criteria of similarity and regularity were determined, physical-chemical model and erosion-corrosion prediction methods was created and also arrangements on improvement of erosion-corrosion durability of national power equipment for Verkhne-Mutnovsky, Mutnovsky GeoPP and GeoPP “San Jasinto” (Nicaragua) were proposed and introduced in Povarov O.A., Tomarov G.V. (1992) and Tomarov G.V. (2001).

As a result of on-site investigations, erosion-corrosion durability of various steels in actual geothermal fluid was determined at experimental stands of Verkhne-Mutnovsky GeoPP. For the first time it was stated that effect of alloy additions upon intensity of steels erosion-corrosion in geothermal environment is not so considerable as for traditional TPPs and NPPs (fig. 5). This is caused by the fact that in geothermal multi-component flows erosion-corrosion is accompanied by inhibitory effect connected with salt deposits formation.

Created physical-chemical model of metal erosion-corrosion in multi-component two-phase flows is based upon modern understanding of erosion-corrosion processes and takes into consideration for the first time the peculiarities of oil transfer and change of local physical-chemical properties and parameters of liquid skin, Povarov O.A., Tomarov G.V. (1992) and Tomarov G.V. (2001).

Calculated erosion-corrosion model became the basis of developed methods for metal selection for manufacturing elements of GeoPP equipment that considers corrosion aggressiveness, phase and regime parameters of working geothermal fluid, international and national experience of geothermal power plants operation.

6. CORROSION SPLITTING OF METAL UNDER PRESSURE

Main reason of failures of turbine working blades and discs is the corrosion splitting of metal under the influence of cyclic tensions (CSP); their development is enabled by chlorides concentration in pittings. As a result of long-term researches of CSP mechanism it was stated that CSP occurs at steam expansion in zone $\Delta T \leq 20K$ till humidity extent $\acute{o} < 3\%$ and is determined by temperature, admixture concentration in liquid phase, local electro-conductivity values and pH, mechanical loads, chemical composition and metal surface condition, Tomarov G.V. and Shipkov A.A. (2002).

Use of stable titanic alloys and chromic steels for manufacturing highly strained turbine details and other GeoPP equipment was restrained by absence of data on their corrosion-fatigue behaviour in geothermal fluid. For solving this problem researches were implemented for studying corrosion-fatigue properties of titanic alloy TS-5 and 15H11MF class steel in the air, in geothermal water with and without presence of hydrogen sulphide.

Modeling geothermal water of Mutnovsky reservoir by chemical composition (805 mg/l $Na_2SO_4 \cdot 1 - H_2O$; 30 mg/l KCl; 25 mg/l $CaCl_2$; 85 mg/l $NaHCO_3$; 5 mg/l $MgCl_2 \cdot 6H_2O$ и 9000 mg/l $NaCl$) and implementing pure bending of rotating specimens with testing base up to $5x10^{-7}$ cycles, data were acquired for the first time on scope of endurance for titanic alloy TS-5 and steel 15H11MF, Povarov O.A. and Tomarov G.V. (1997). Researches allowed determining that scope of endurance for titanic alloy in the air is at the level of 280 MPa. Proportion of scope of endurance and scope of durability during alloy stretching is just 0,32 $\sigma_и$ ($\sigma_и$=872 MPa).

Testing of alloy TS-5 in geothermal water showed decrease of scope of endurance of specimens by 11% ($\sigma_и^{corr}$ =250 MPa). Combined effect of geothermal water and hydrogen sulphide leads to additional decrease of TS-5 scope of endurance by 12% (σ_{-1}^{corr} =220 MPa) in comparison with testing in geothermal water and by 22% in comparison with experiments in the air (fig. 6, a).

Results of fatigue testing of specimens of steel 15H11MF are presented at fig. 6, b. In geothermal water conditional scope of endurance is established at the level of 90 MPa, i.e. scope of endurance decreased by 77% in comparison with experiments in the air. At presence of hydrogen sulphide in geothermal environment scope of endurance for steel 12H11MF was not detected at all even after 80% of durability decrease. Steel 12H11MF proved to be more sensitive towards laying of tension concentrator than TS-5.

Implemented researches give the evidence of necessity of considering scope of endurance decrease of steels in geothermal environment and advisability of using titanic alloy TS-5 for manufacturing GeoPP turbine working blades.

7. MOISTURE SEPARATION

Urgency of creating highly effective separation facilities for GeoPP is determined by high mineralization of geothermal fluid and presence of admixtures causing corrosion, erosion of metal and salt deposits in power equipment elements, in its composition.

Most effective is the gravitational separation that is used in modern facilities during separation of liquid phase from humid steam flow. Such facilities are remarkable for relative design simpleness and high separation effectiveness.

Calculations show that at pressure 0,6-1,0 MPa and steam speed 0,7 m/s humidity extent caused by transported carry-over is 0,1% at the most.

For confirming calculated technical characteristics of separators included into steam preparation system at Verkhne-Mutnovsky GeoPP, experimental researches were conducted at model separator that was created in MPEI and represented model of on-site separator diminished on scale 1 : 4,62, and in on-site conditions of Mutnovsky reservoir.

Experimental investigations of gravitational separator model, Semenov V.N. et al. (2002), showed that at calculated loads one of main separator conditions for volume is realized – speed in medium profile does not exceed 1 m/s.

On-site testing of moisture removal effectiveness and pressure losses in separators were implamented at pilot Verkhne-Mutnovsky GeoPP (fig. 7). Steam humidity during this testing was determined by salt method, as a proportion (1) of measured sodium ions in steam and liquid phases after separator.

$$Y = C_{ï}^{Na} / \tilde{N}_{â}^{Na} = 10^{((pNa)â-(pNa)ï)} \qquad (1)$$

Implemented testing showed that steam humidity at separator outlet are 0,05% at the most at all calculated working regimes, with minor (5KPa at the most) pressure losses. These indices are essentially higher than for cyclone type separators, and this provides reliable turbine operation without danger of salt covering of flow part and corrosion-erosion effect of geothermal steam upon metal.

CONCLUSION

The bottom line of theoretical and experimental investigations is developing of geothermal engineering industry for creation of modern geothermal power plants.

Complex experimental and theoretical researches that were implemented provided creation of national highly effective geothermal power equipment and construction of Verkhne-Mutnovsky GeoPP, Mutnovsky GeoPP and GeoPP San Jasinto (Nicaragua). Eight electric and thermal power plants are successfully operating on Kamchatka and Kuril Islands.

REFERENCES

Povarov O.A., Tomarov G.V. Physical-technical problems of geothermal energy // Izvestiya RAN. Energy. – 1997 – No 4. – P. 3-17 (in Russian)

Povarov O.A. Formation of aggressive environments in steam and problems of metal erosion-corrosion // Preprint. Novosibirsk, 1988 – No 173. 39 pp. (in Russian)

Povarov K.O. Impurities distribution between steam water phases for geothermal power plant // 22nd New Zealand Geothermal Workshop.2000. P. 181-189.

Filippov G.A., Povarov O.A., Nikolsky A.J. The Steam Flow Discharge Coefficient and Losses in Nozzles of a Steam Turbine Stage Operating in the Low Steam

Wetness Zone // Aero-Thermodynamics of Steam Turbines. 1981. P. 37-42.

Povarov O.A., Ignatyevskaya L.A., Semenov V.N. Peculiarities of transfer process in turbo-machines channels during transition across saturation line // Heat and mass exchange in power devices. Vol. 8. Minsk, 1984. P. 39-46 (in Russian)

Deych M.Ye., Povarov O.A., Troitsky A.N., Kurshakov A.V. Experimental temperature characteristics of surface nozzle blades in wet steam // Izvestiya AN SSSR, Ser. Energy and Transport. 1990. No 3. P. 36-39 (in Russian)

Povarov O.A., Rabenko V.S., Semenov V.H. Influence of admixtures in steam upon formation of liquid phase in turbines /Teploenergetika. 1984. No 3. P. 36-39 (in Russian)

Martynova O.I., Povarov O.A., Semenov V.N. et al. Formation of corrosion-active environments in phase transition zone of steam turbines // Teploenergetika. 1998. No 7. P. 37-42.

Povarov O.A., Feldberg L.A., Semenov V.N., Popov S.A. Measurement of dispersion and steam humidity in turbine using spectral transparency method//Teploenergetika. No 2. 2000. P. 34-38.

Semenov V.N., Troitsky A.N., Popov S.A., Agapov R.V. Experimental plant for research of processes of formation and concentration of corrosion-aggressive environments in phase transition zone for steam turbines // Vestnik MEI. 1999. No 5. P. 5-10 (in Russian)

Povarov O.A., Semenov V.N., Troitsky A.N. Formation of liquid skins and corrosion-aggressive environments at blades and discs of turbine stages // Proceedings of EPRI meeting on corrosion of blades and discs of steam turbines in phase transition zone, EPRI, Palo Alto, CA, USA, 1998. P. 409 - 420.

Povarov O.A., Tomarov G.V. Problems of multi-phase environments of geothermal fluids // Teploenergetika – 1992. No 5. P. 66-70 (in Russian)

Tomarov G.V. Physical-chemical processes and regularities of metal erosion-corrosion of power equipment in two-phase flow // Teploenergetika. 2001. No 9. P. 59-67 (in Russian)

Tomarov G.V., Shipkov A.A. Modeling of physical-chemical processes of metals erosion-corrosion in two-phase flows // Teploenergetika. 2002. N0 7. P. 7-17 (in Russian)

Semenov V.N., Ageyev A.G., Troitsky AS.N. et al. Investigation of environment flow processes in horizontal moisture separator // Tyazheloye mashinostroyeniye. 2002. No 8. P. 27-31 (in Russian).

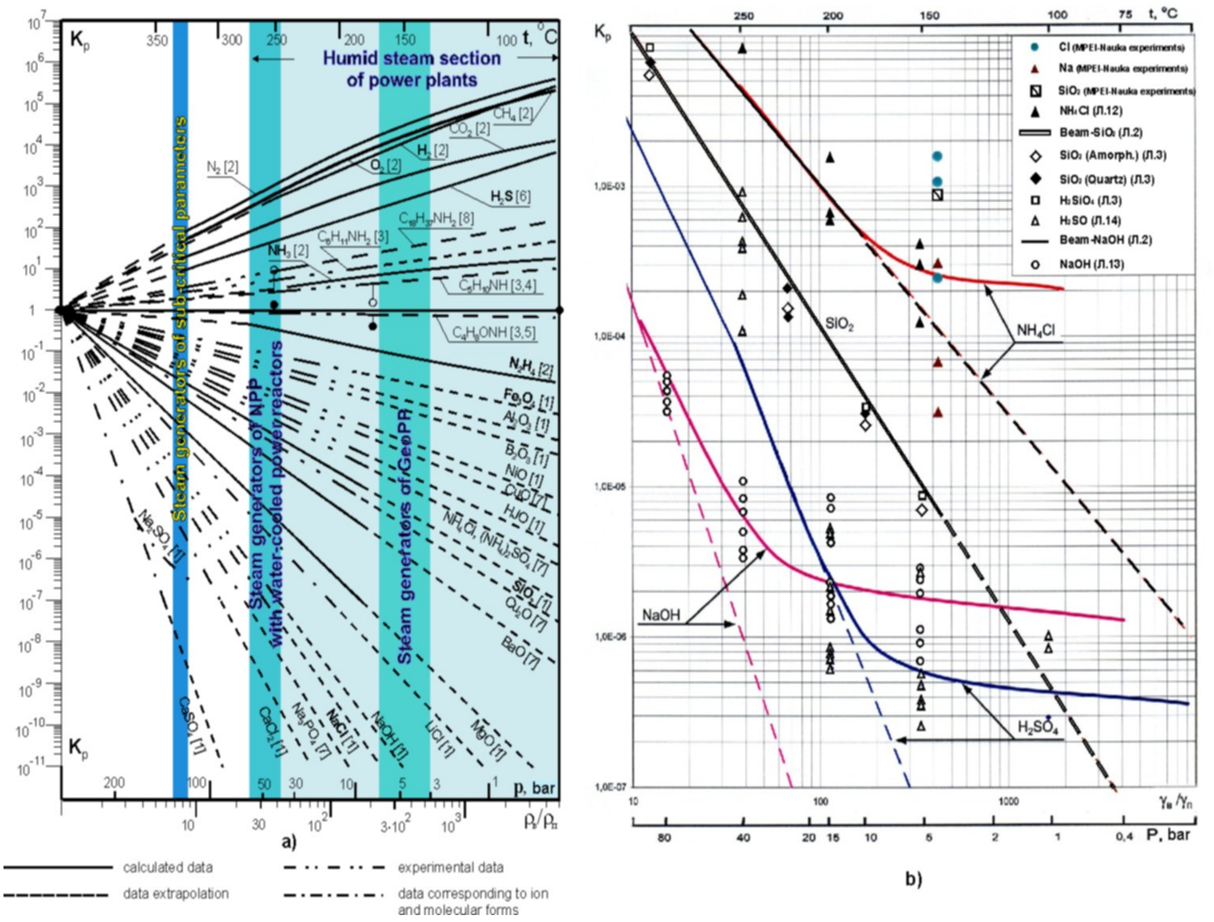


Figure 1: Radial diagram of balanced coefficients of inter-phase admixtures and gases distribution (Cb) between liquid and steam phases (a) and results of on-site investigations of Cb values for corrosion-aggressive admixtures (b).

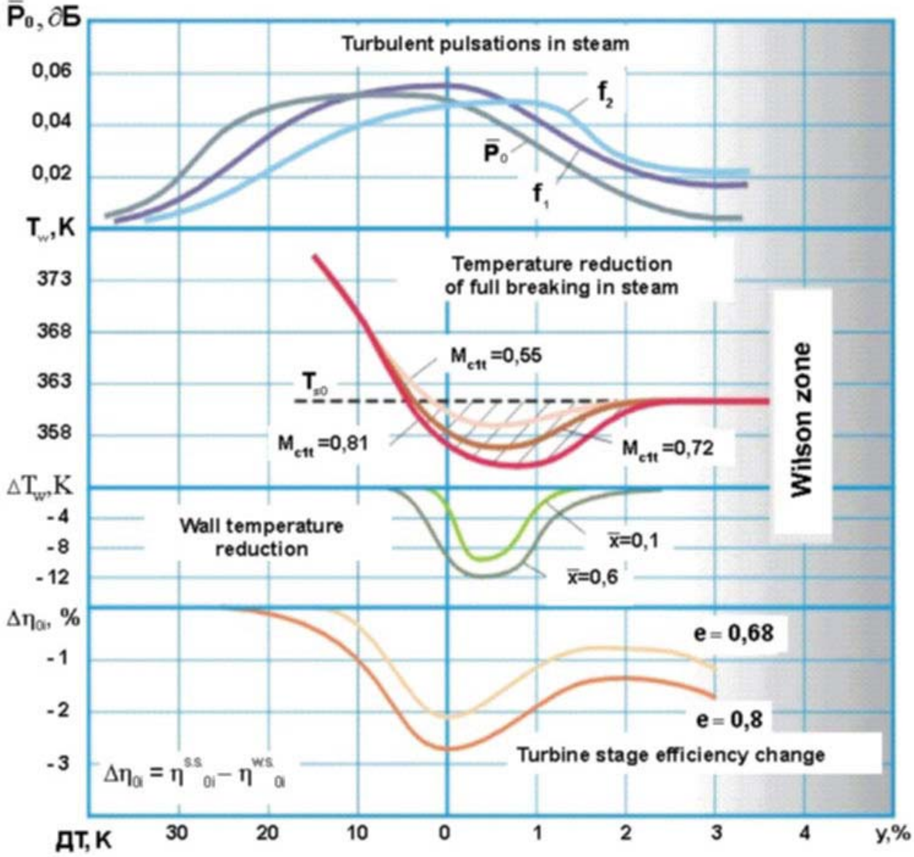
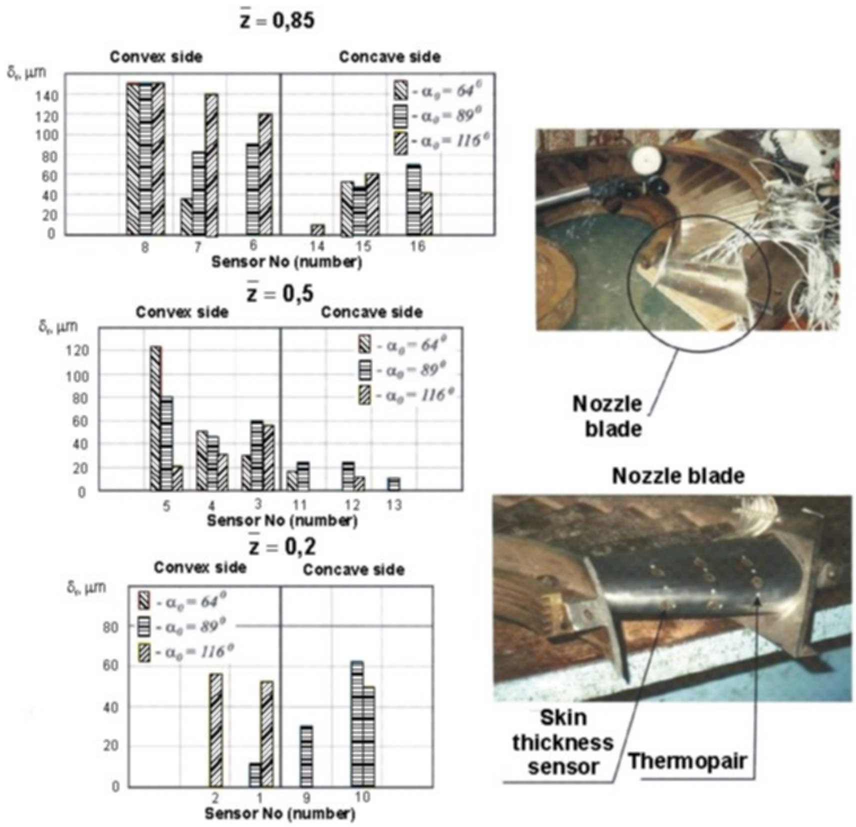


Figure 2: Research of crisis phenomena in steam in border curve zone.



a) b)

Figure 3: Influence of inleakage angle upon thickness of liquid skins upon surfaces of nozzle blade (a); nozzle blades with sensors of skin thickness and thermopairs (b).

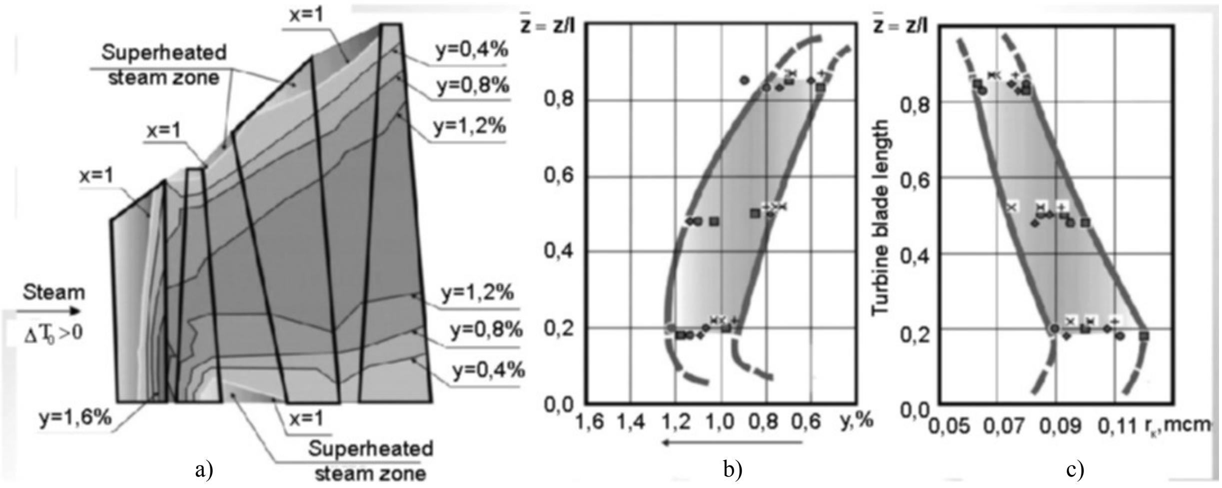


Figure 4: Results of calculation of condensing steam flow – in experimental turbine a), of measurements of humidity extent b) and dispersion c) after turbine 1st stage.

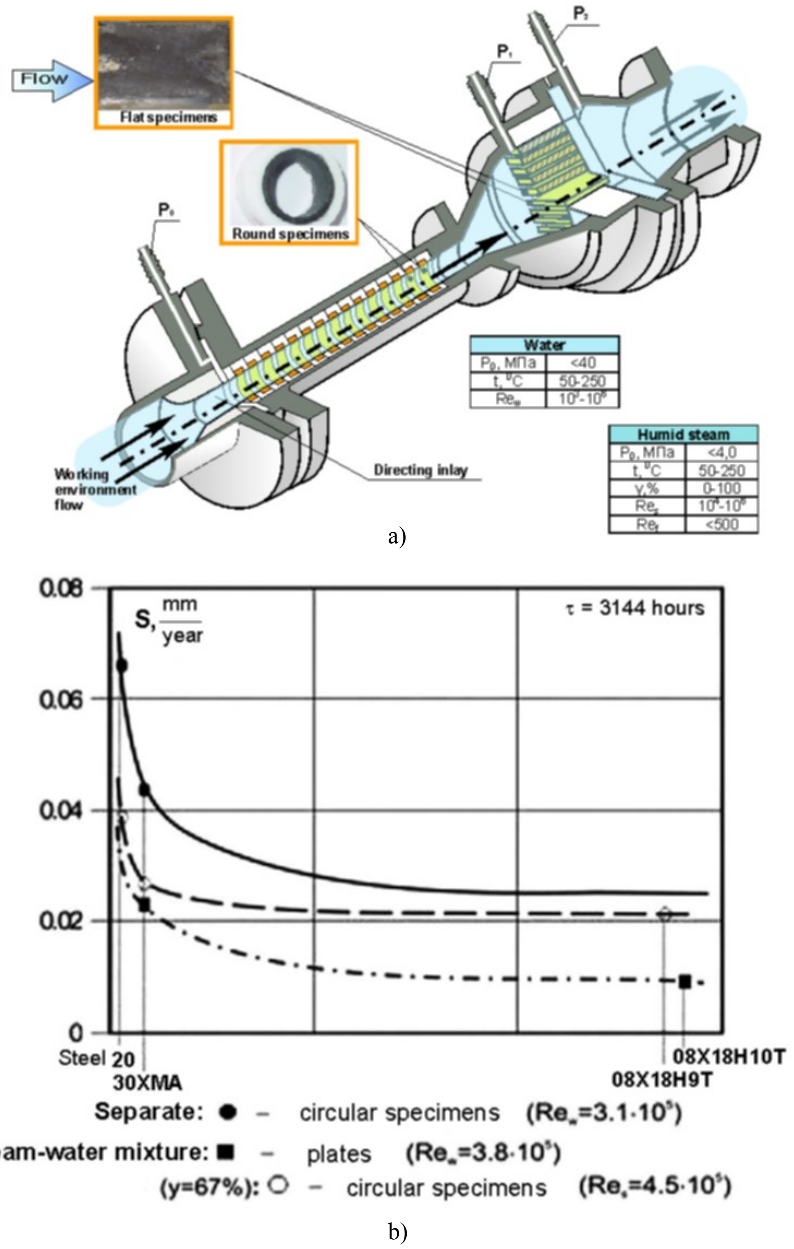


Figure 5: Experimental erosion-corrosion test-module (a) and results of on-site investigations of influence of alloying admixtures upon intensity of steels erosion-corrosion in geothermal single- and two-phase flows (b).

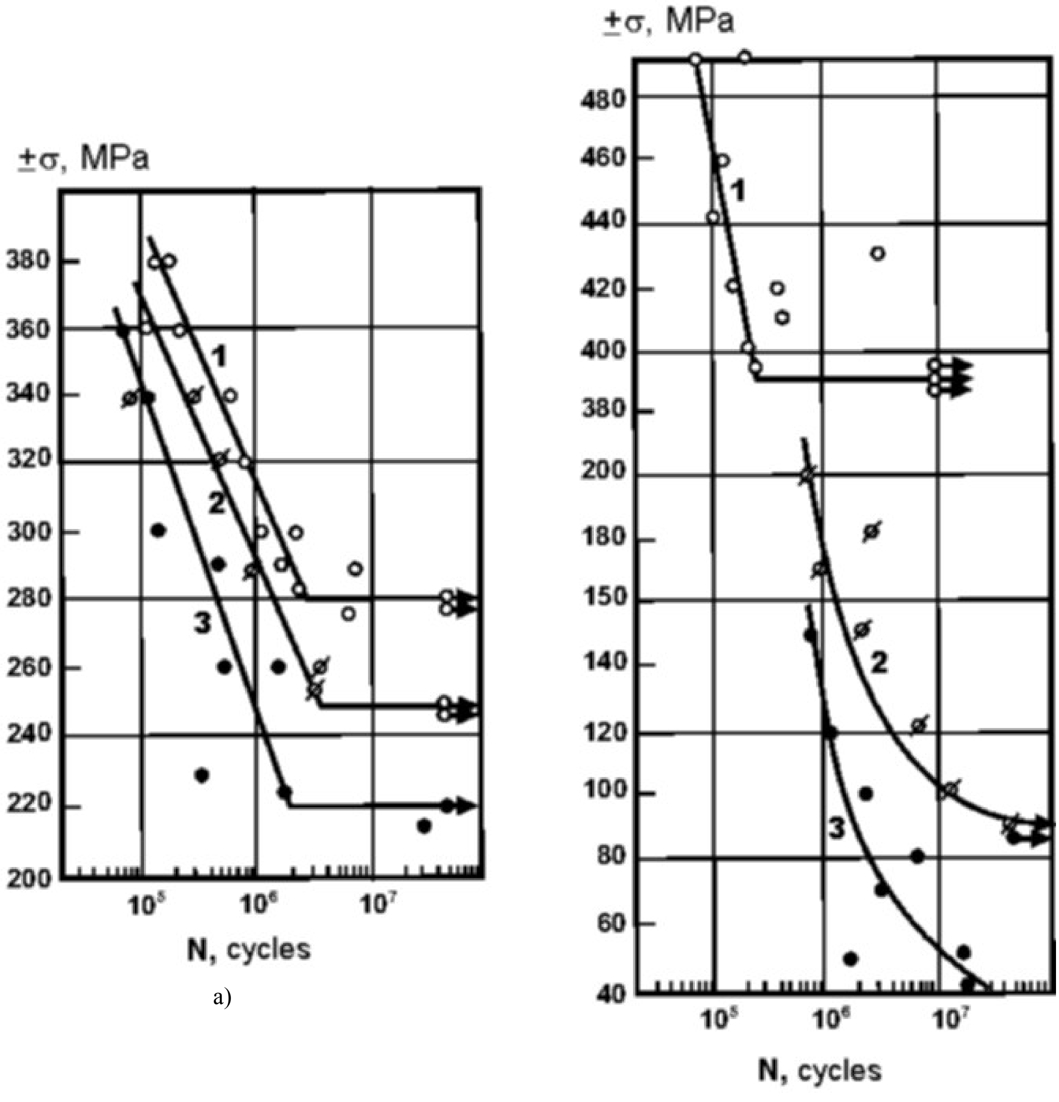


Figure 6: Fatigue properties of smooth specimens of titanic alloy TS-5 (a) and steel 15H11MF (b) in the air (1), in geothermal environment (2) and in geothermal environment with hydrogen sulphide (3).

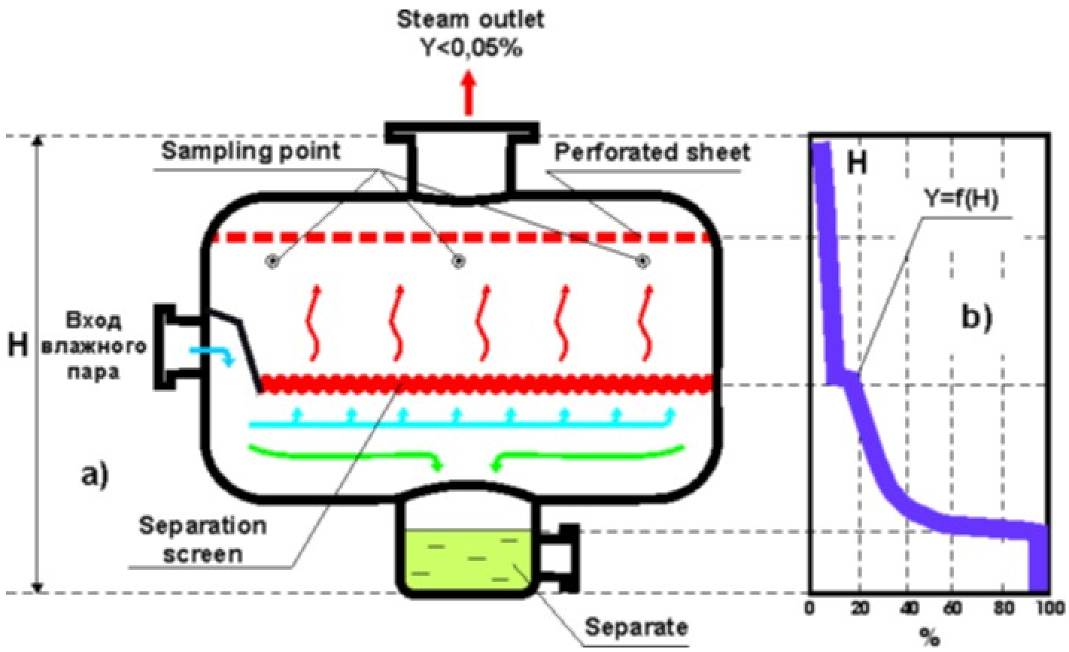


Figure 7: Principal scheme of separator VM GeoPP (a) and results of humidity measurements by separator height (b).