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PRACTICAL EXPERIENCE WITH THE INTRODUCTION OF HONEYCOMB SHROUD SEALS ON 250 – 800 MW SUPERCRITICAL PRESSURE UNITS

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Practical experience with the introduction of honeycomb seals in the flow-through sections of 250 – 800 MW steam turbines with supercritical steam pressure is examined. The most widespread designs for shroud and end honeycomb seals used in the development of new turbine units are discussed, along with the modernization of existing steam turbine equipment. Test stand data on the relative flow rate and power characteristics of honeycomb, radial, and axial-radial seals are compared. Results are reported from thermal tests for evaluating the efficiency of installing honeycomb shroud seals in the high pressure cylinders of the T-250/300-240 turbine units at the TÉTs-21 plant of JSC "Mosénergo" and the K-800-240-5 turbine units at the Perm GRÉS plant of JSC "OGK-1."

Keywords: honeycomb seal; steam turbine; turbine unit; efficiency; flow-through section; thermal tests; supercritical pressure; flow rate and power characteristics; low-frequency vibration.

One of the tasks in improving the thermal-mechanical and operational performance of existing steam turbine equipment is modernization of the flow-through sections using improved designs for seals with a honeycomb surface. The relative internal efficiency of the high pressure cylinder has been increased by 0.6 – 1.7%, just by reducing the radial gaps during installation of honeycomb shroud seals, with the maximum increase attained when all stages of the cylinder are equipped, including the regulator.

Design of honeycomb seals used in modernizing the flow-through sections of 250 – 800 MW steam turbines. Over the last decade the firm ARMS (Moscow), together with the manufacturers of steam turbines JSC "Power Machines" (St. Petersburg) and JSC "UTZ" (Yekaterinburg) have used the production facilities of JSC NPP "Motor" (Ufa) to develop and introduce honeycomb shroud and end seals for 250 – 800 MW turbine units.

Some of the basic designs for honeycomb seals currently in use in the flow-through sections of turbine units with supercritical steam pressure are shown in Fig. 1.

Seals of the types shown in Fig. 1*a* and *d*, are installed on more than 170 steam turbines of types T-100-130, K-200-130, PT-60-130, and PT-80-130 and modifications of these.

In order to increase the reliability and optimize the honeycomb seal design, JSC "Power Machines," NPP "ARMS," and NRU "MPEI" have carried out test stand studies of wear in seal components (rotor collar and honeycomb assemblies with cell diameters of 0.9, 1.1, and 1.5 mm) in mutual contact. The tests were done in various rotational modes (2 – 1600 rpm) with a maximum incision depth of 4.0 in the honeycomb surface.

An analysis of the data shows that the honeycomb assemblies with cell diameters of 0.9 – 1.5 mm and wall thicknesses of 0.05 mm are quite "soft" and easily cut during contact, while the rotor collars undergo minimal abrasion without signs of heating (no temper color). No removal or flaking of the honeycomb surface was observed after the tests.

Honeycombs with cell sizes of 1.5 mm were chosen as preferable for breaking in the honeycomb surface for further use in the flow-through sections of steam turbines.

Figure 2 shows some pictures of the yoke of the regulator stage of the high pressure cylinder and the diaphragm of the medium pressure cylinder of a K-200-130 turbine unit in which the most typical wear of the honeycomb and traditional radial seals can be seen. During initial startup of one of the turbine units as it was being overhauled, increased vibration of the high and medium pressure rotors (unassociated with the installation of honeycomb seals) up to levels of 11.2 mm/sec was detected. An inspection of the shroud seals of the flow-through section of the high pressure cylinder revealed the presence of contact wear of the honeycomb surface by up to 3 – 4 mm in the radial direction and 1 – 2 mm

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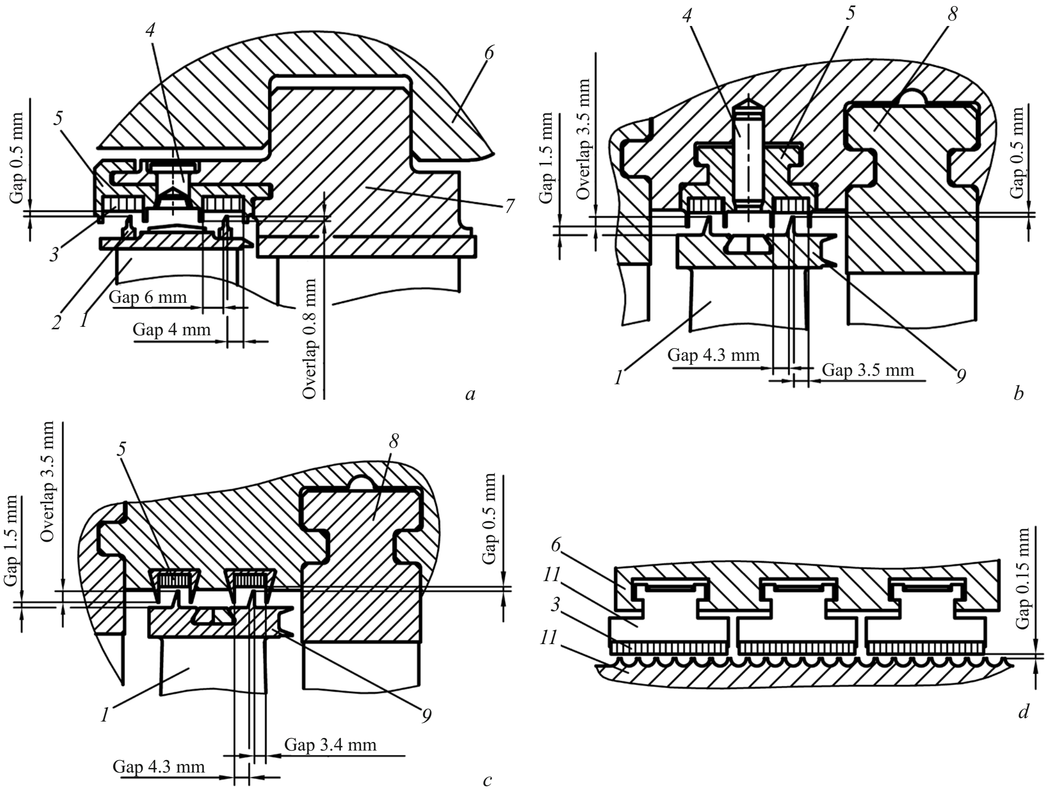

Fig. 1. Honeycomb shroud seals for the high and medium pressure cylinders of T-250/300-240 (*a*), K-300-240 and K-660-240 (*b*), K-300-240, K-330-240MR, and K-800-240 (*c*) turbine units and for the medium pressure cylinder TsSD-2 and the low pressure cylinders of a T-250/300-240 turbine (*d*): *1*, rotor blade; *2*, rotor collar; *3*, honeycomb assembly; *4*, pin; *5*, honeycomb insert; *6*, yoke; *7*, diaphragm; *8*, director blade; *9*, blade shroud; *10*, rotor bushing; *11*, segment of a honeycomb end seal.

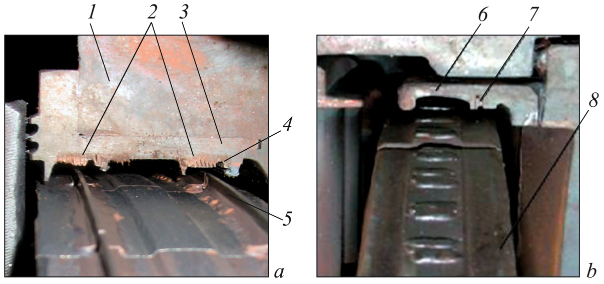

Fig. 2. A honeycomb shroud seal for the flow-through section of the high pressure cylinder (*a*) and a radial shroud seal for the flow-through section of the medium pressure cylinder (*c*) of a K-200-130 turbine unit after contact wear: *1*, yoke of regulator stage; *2*, honeycomb assembly; *3*, honeycomb seal; *4*, depletion of honeycomb surface; *5*, shroud collar; *6*, diaphragm; *7*, stator collar (100% wear); *8*, blade shroud.

Fig. 3. Honeycomb end seal of the low pressure cylinder of a T-250/300-240 turbine unit after 5 years of operation: *1*, yoke; *2*, seal segment; *3*, rotor collar; *4*, wear of honeycomb surface.

axially. No wear was observed in the rotor shroud collars at the time.

In this same case, complete abrasion of the seal collars of the traditional flow-through seals located at the diaphragm of the medium pressure cylinder was observed.

Figure 3 shows the honeycomb end seals of the low pressure cylinder of a T-250/300-340 turbine unit after 5 years of operation. The honeycomb surface was worn radially by up to 1.0 – 2.5 mm and axially by up to 3.5 – 4.0 mm. There was no temper color. The wear of the honeycomb surface in the axial direction corresponds to the relative displacements of the rotor. The state of the honeycomb surface was found to be satisfactory upon inspection and the seal was approved for further use without replacement and repair [1].

Operating experience with T-250/300-240 turbine units in the JSC “Mosénergo” system [2] also confirms the effectiveness of using honeycomb end seals for the medium pressure cylinder TsSD-2 and the low pressure cylinder: the operation of the ejectors became normal and the amount of water in the oil was reduced, and the range of relative displacements of the medium pressure rotor RSD-2 was expanded.

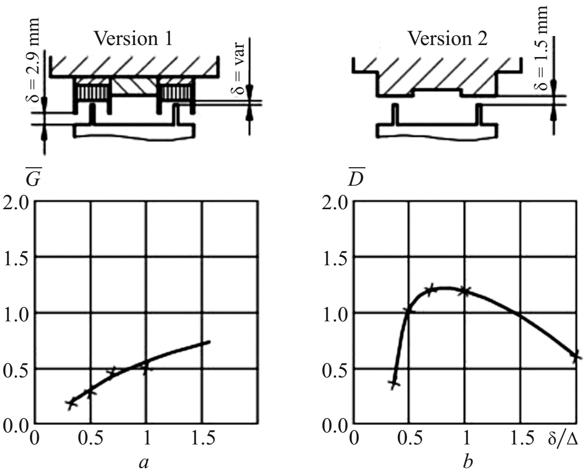

Fig. 4. Plots of the ratios of the flow rate $\overline{G}$ (*a*) and power $\overline{D}$ (*c*) characteristics of honeycomb and radial seals: δ, the gap in the seal; $D = 1$ mm, the collar thickness.

Wear of the honeycomb surface generally occurs during transitional modes of operation of a turbine unit (cold startup, passes through critical frequencies of the shaft line, stopping, etc.), when the seal components of the flow-through section occupy an intermediate position relative to one another. During steady-state operation of the turbine the rotor collars occupy their working position (which differs from the intermediate position) above a part of the honeycomb surface with no wear. The flow of steam through the honeycomb seals essentially does not increase, and both the shroud and end seals continue to operate efficiently with the minimum permissible gaps.

Based on a large amount of statistical data obtained during inspection of the flow-through sections of steam turbines, technical specifications have been developed for the use of operating personnel at power plants and in agreement with JSC "Power Machines" and JSC "UTZ" for evaluating the state of shroud, diaphragm, and end honeycomb seals which establish the order of fault detection, tolerance criteria for further operation, and, when necessary, the amount and type of repair and recovery measures to be undertaken during major overhaul of turbine units.

Results of the test stand studies. In order to optimize the geometric dimensions of the honeycomb cells and determine the minimum permissible gaps in the shroud seals of the flow-through sections of supercritical pressure turbine units tests were made on the stands at the A. V. Shcheglev Dept. of Steam and Gas Turbines at the Moscow Power Engineering Institute together with JSC "Power Machines" and NPP "ARMS" to study the power and flow-rate performance of honeycomb, radial, and axial-radial shroud seals that were identical in terms of their geometrical characteristics to those used in the flow-through sections of steam turbines [3, 4]. For a correct comparison, all the data were reduced to unified initial flow parameters (initial pressure ahead of the seals $P_0 = 124$ kPa, temperature ahead of the seals $t_0 = 32$°C, tangential component of the flow velocity at the seal inlet $C_0 = 42$ m/sec, ratio of the pressure after the seal to that before the seal $\varepsilon = 0.806$).

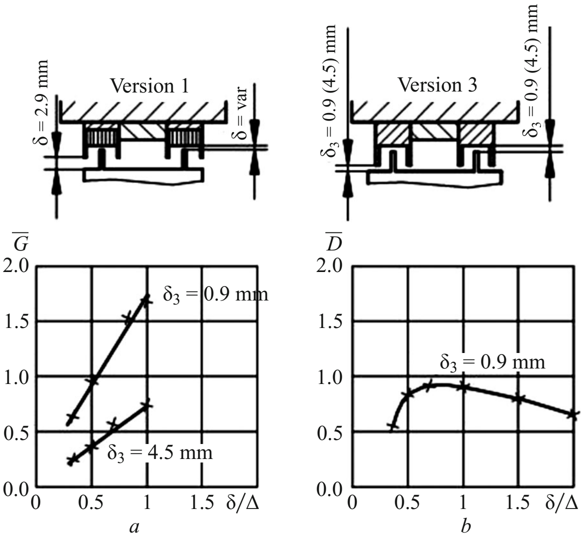

Fig. 5. Plots of the ratios of the flow rate $\overline{G}$ (*a*) and power $\overline{D}$ (*c*) characteristics of honeycomb and axial-radial seals: notation as in Fig. 4.

The plots in Fig. 4 of the relative (to the calculated value) flow rate $\overline{G}$ and relative rigidity $\overline{D}$ of the nonconservative aerodynamic force were obtained for $\delta_{\text{var.1}} = \text{var}$ and $\delta_{\text{var.2}} = \text{const} = 1.5$ mm, where version 1 is identical to the honeycomb shroud seal for the high pressure cylinder of T-100-130, PT-60-130, K-200-130, K-300-240, and K-660-240 turbines and version 2 corresponds to the radial seals traditionally used in the high pressure cylinders of PT-60-130, R-50-130, and K-200-130 turbines.

An analysis of the curves in Fig. 4 shows that the flow *G* through a honeycomb seal with a working gap of $\delta = 0.5$ mm is 40% of the flow through a radial seal with a working gap of 1.5 mm. The rigidity of the aerodynamic nonconservative force *D* of the honeycomb seal for gaps smaller than 0.5 mm has a tendency to fall off rapidly compared to the rigidity of a flow-through seal with a radial gap of $\delta = 1.5$ mm.

The plots of relative flow rate $\overline{G}$ and relative rigidity $\overline{D}$ for the nonconservative aerodynamic force shown in Fig. 5 were obtained for $\delta_{\text{var.1}} = \text{var}$ and $\delta_{\text{var.3}} = \text{const} = 0.9$ (4.5) mm (two axial-radial seals with gaps over the sealant surface of 0.9 and 4.5 mm were studied). Here version 3 is identical to the shroud axial-radial seals employed in the high pressure cylinders of T-100-130, K-300-240, and T-250-240 turbines.

The flow through the honeycomb seal with a working gap of $\delta = 0.5$ mm is essentially equal to the flow through an axial-radial seal with a working radial gap of 0.9 mm; here the rigidity of the nonconservative component of the aerodynamic force for the honeycomb seal is lower by 10 – 15% than that for the axial-radial seal. The flow through the

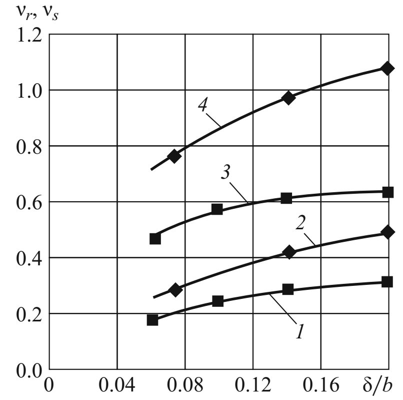

Fig. 6. Parameters of the vortex on the stator (v_s) and rotor (v_r) surface of the seals: *1*, *3*, v_r and v_s for a honeycomb seal, respectively; *2*, *4*, v_r and v_s for a seal with smooth walls, respectively; *d*, the gap in the seal; $b = 5$ mm, the height of the seal chamber.

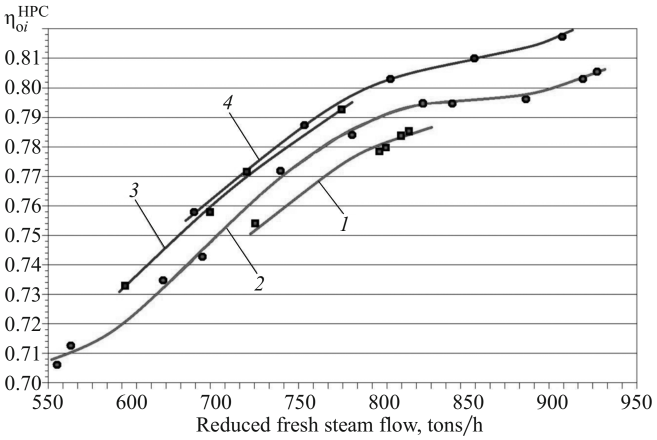

Fig. 7. The variation in the internal relative efficiency of the high pressure cylinder of the T-250/300-240 turbine at unit No. 8 of the TÉTs-21 plant of JSC "Mosénergo" before and after installation of honeycomb shroud seals: *1*, *2*, operating with the high pressure preheater turned off and on, respectively (first stage of the tests); *3*, *4*, operating with the high pressure preheater turned off and on, respectively (second stage of the tests); the flow rate is reduced to the nominal fresh steam pressure (23.5 MPa) and temperature (540°C).

honeycomb seal with a working gap of $\delta = 0.5$ mm is 40% of that through an axial-radial seal with a gap of 4.5 mm.

During the experiments a pneumometric probe was used to measure the velocity and direction of the flow in the shroud chamber at the boundaries of the stator and rotor. A comparison of the vortex parameters (v_r, v_s) yields the following conclusion: in the honeycomb seal the vortex intensity is substantially lower than in a seal with smooth walls for the shroud chamber. Under some operating conditions the reduction was up to 30%. For small radial gaps ($\delta \le 0.5$ mm) a near channel flow developed in the chamber. A reduction in the difference between the absolute values of v_r and v_s in the honeycomb seals was detected over the entire range of relative gaps compared to seals with a smooth wall (Fig. 6).

It appears that the increased roughness of the honeycomb surface causes a considerable reduction in the tangential component of the flow in the shroud chamber (aids in quenching the vortex) and, therefore, reduces the nonconservative component of the aerodynamic force, thereby confirming that using a honeycomb surface in a shroud seal is not the destabilizing factor that facilitates the development of low-frequency vibration of the rotor [4].

Results of thermal tests of a T-250/300-240 unit at JSC "Mosénergo." In the 1970's during industrial introduction of the type T-250-240 turbine at "Mosénergo" it was found that low-frequency vibration of the high pressure rotor developed as the turbine reached its threshold power [5]. This was eliminated after installing vibration resistant axial-radial shroud seals with radial gaps of 4.5 – 5.0 mm along the seal surface that had been proposed by JSC "UTZ."

Operating experience with honeycomb seals on various types of steam turbines [6] including supercritical steam systems with reactive blading (K-330-240MR, K-660-240), together with an analysis of the experimental data have made it possible for experts at NPP "ARMS" to develop and agree with JSC "UTZ" a design for honeycomb shroud seals for high pressure cylinders with radial gaps of 0.5 – 0.7 mm. The design solutions shown in Fig. 1*a* have been installed in stages 2 – 12 of the high pressure cylinders of four T-250/300-240 turbines: units No. 8 and 9 at the TÉTs-21 plant, unit No. 3 at the TÉTs-26 plant, and unit No. 6 of the TÉTs-25 plant, all of JSC "Mosénergo."

The work was done by the power plant overhaul company "TÉR-Moskva."

Besides the honeycomb shroud seals for the high pressure cylinders, in order to improve the maneuverability of the above listed turbines and to prevent suction into the vacuum system, honeycomb end seals have been installed in the collars of the medium pressure cylinder TsSD-2 and the high pressure cylinder with gaps over the sealing surface of 0.15 – 0.20 mm. To create additional expansion chambers and eliminate thermal fatigue of the surface layer of the metal, the fitting bushings of the rotors were bored out on the recommendation of JSC "UTZ" (Fig. 1*d*).

Experts from the Moscow branch of JSC " Southern Power Engineering Center" have carried out thermal tests to evaluate the efficiency of introducing honeycomb shroud seals on the T-240/300-240 turbine at unit No. 8 of TÉTs-21.

Figure 7 is a plot of the variation in the internal relative efficiency of the high pressure cylinder (η_{oi}^{HPC}) as a function of the fresh steam flow rate in this turbine.

Over the entire range of steam load η_{oi}^{HPC} was found to increase from 1.25% for a fresh steam flow of 640 tons/h to 1.68% for loads close to maximal (910 tons/h), which corresponds to an increase in the power of the high pressure cylinder power by roughly 1.5 MW. According to the manufacturers calculations an increase of 0.7 – 1.0% in the efficiency was expected. No other work besides installing the honeycomb shroud seals for stages 2 – 12 was done during the

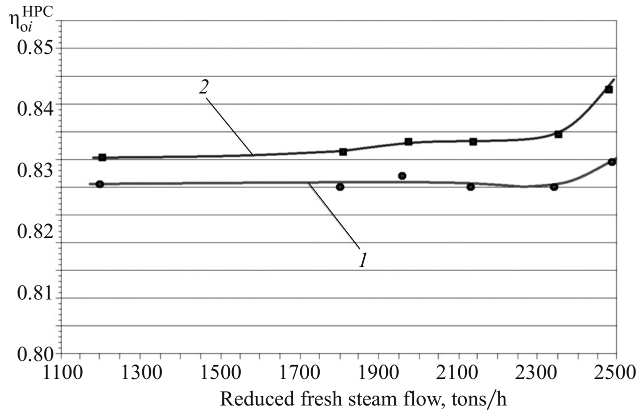

Fig. 8. The variation in the internal relative efficiency of the high pressure cylinder of the K-800-240-5 turbine at unit No. 8 of the Perm GRÉS plant of "OGK-1" before and after installation of honeycomb shroud seals: *1*, *2*, first and second stages of the tests; the flow rate is reduced to the nominal fresh steam temperature (540°C).

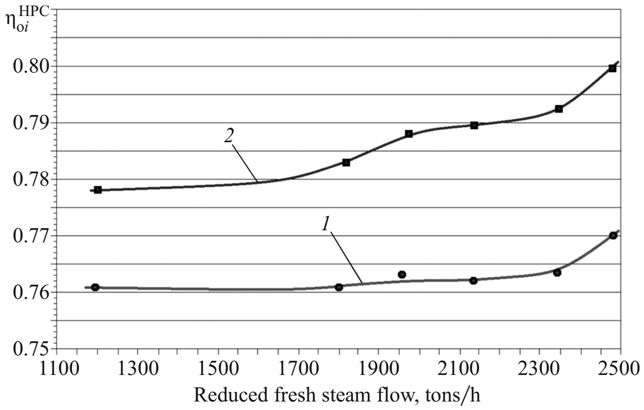

Fig. 9. The variation in the internal relative efficiency of the high pressure cylinder at cutoff of the "stage 9 automatic shutoff valve" of the K-800-240-5 turbine at unit No. 1 of the Perm GRÉS plant of "OGK-1" before and after installation of honeycomb shroud seals: *1*, *2*, first and second stages of the tests; the flow rate is reduced to the nominal fresh steam temperature (540°C).

overhaul that could influence the change in the relative internal efficiency of the high pressure cylinder.

Another criterion for determining the effectiveness of updating the turbine is to estimate the change in the steam leakage into the flow-through section of the high pressure cylinder based on the discrepancy between the dependences of the internal relative efficiency of the high pressure cylinder in experiments with and without regeneration installed [7]. The discrepancy in the values of η_{oi}^{HPC} before reconstruction was about 1.1%; after reconstruction it did not exceed 0.2%, which means that the total leakage at the shrouds was reduced.

During modernization of the high pressure cylinder with a reduction in the radial gaps in the shroud seals in order to maintain vibration resistance of the shaft line of the turbine unit over the entire range of loads, it was especially important to take special care in the repair operations in the course of assembling the turbine unit while following the specifications and recommendations of the manufacturer, in particular:

— centering the elements of the flow-through section of the cylinder with statements of the specified radial and axial gaps, taking into account possible warping of the collars and of the inner high pressure cylinder;

— centering of the rotors with respect to bores and half-clutches;

— alignment of the slopes of the rotors with respect to the bearing pins and uniform distribution of the load over the shaft support taking into account their displacements during changes in the thermal state of the turbine; and,

— repair of the bushings, and checking and fitting of the gaps in the support bearings of the turbine.

After reconstruction of four modernized T-250/300-240 turbines, low frequency vibration was either entirely absent in the high pressure rotor bearings (including in nominal operation with $N = 250$ MW and $G = 900$ tons/h) or did not exceed a level of 0.1 mm/secec, in full agreement with the specifications [8].

Similar results were obtained in tests after installation of honeycomb shroud seals in stages 3 – 10 of the high pressure cylinder of the K-800-240-5 turbine at unit No. 1 of the Perm GRÉS plant. Their design is close to that shown in Fig. 1*c* (the tests were done by the Moscow branch of the JSC "SCPE").

Figure 8 shows that the internal relative efficiency of the cylinder increased over the entire range of fresh steam flows. The largest increase of 1.28% (about 3.8 MW) was recorded for nominal operation of the turbine unit (N = 800 MW, $G = 2500$ tons/h).

The variations in η_{oi} at the cutoff of the "stage 9 automatic shutoff valve" with modernized shroud seals for all stages were still higher within the range of fresh steam flows (1150 – 2480 tons/h) at 1.7 to 2.9% (Fig. 9).

The lower absolute magnitude of the efficiency of this cutoff compared to the efficiency of the entire high pressure cylinder is explained by the influence of the regulator stage that is unequipped with honeycomb seals and has a specific weight in the temperature drop for the "stage 9 automatic shutoff valve" that is considerably higher than for the cylinder as a whole.

The experimental data shown here confirm the calculated increase in η_{oi}^{HPC} by 0.5 – 0.7% obtained by experts at the firm SKB "Turbina" with hydrodynamic modelling of the leakage through honeycomb shroud seals for actual radial gaps set within the range $\delta = 0.95 – 1.18$ mm with centering of the flow-through section of the high pressure cylinder of this turbine at the Perm GRÉS.

About half the total increase in the internal relative efficiency of the high pressure cylinder by 1.28% may be attributed to the effect of modernizing the shroud seals, while the rest of the increase is the result of the repairs made on the high pressure cylinder during the major overhaul.

CONCLUSIONS

1. The designs for honeycomb shroud and end seals reported here can be installed in the flow-through sections of 250 – 800 MW supercritical-pressure turbine units.

2. Honeycomb seals provide higher internal relative efficiency of the high pressure cylinders than the traditional forms of seals employed in steam turbines.

3. When the developer's recommendations are followed, the installation of honeycomb shroud seals in the high pressure cylinders of 250 – 800 MW turbine units does not lead to low frequency vibrations of the high pressure rotor.

Experience also shows that in order to provide for prolonged reliable operation of honeycomb seals, as of any seals with small gaps, the design of steam turbines must provide for concentricity of the cylinders and rotors during prolonged operation, different operating conditions, and changes in load.

Suitable operational measures must also be taken to ensure high purity of the steam fed into the turbine and that there are no particles formed by corrosion or oxidation in the steam.

4. Given the positive experience with the introduction of honeycomb designs, it is appropriate to test them in the regulator stage, as well as in the end and intermediate seals of the high pressure cylinders of supercritical steam turbines and to plan for their use in the development of the flow-through sections of new high unit power turbine units, including those with supercritical steam ($t = 600 – 620°\text{C}$, $P \leq 29$ MPa).

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