Development of scroll vacuum pump characteristics by thermal deformations compensation

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Abstract. Influence of thermal deformations of scroll vacuum pumps working elements on clearances in working mechanism is considered. Analysis of influence of a clearance value on indicator diagrams and pumping speed was carried out. It is shown that alteration of a clearance due to thermal deformations decreases pumping speed at low pressures. The design of scroll elements compensating clearances alteration in pump operation and improving pumping characteristics is presented.

1. Introduction
Scroll vacuum pump (SVP) is one of the most well-known vacuum pumps for oil-free medium and rough pumping. Quietness, non-vibration, constant pumping speed in a wide range of pressures, operation simplicity and high compression ratio make SVP a favorite among vacuum pumps for pumping analytical and medical equipment and different nanotechnological systems.

Backward leakage is one of the main factors determining pumping characteristics of non-contact pumps. In a scroll pump (figure 1) the source of backward leakage is clearances between walls and faces of orbiting and fixed scroll elements. Due to double layer fluoroplastic seals [1] face leakage can be minimized. Existence of radial clearances is indispensable condition for non-contact motion of the orbiting scroll elements. To obtain the ultimate pressure of 1 Pa clearances should be 80–150 μm depending on scroll dimensions. The radial clearance increase by 50 μm results in approximately tenfold ultimate pressure increase [2]. That is why radial clearance minimization (when scrolls contact absence is guaranteed) is urgent task.

For analysis of operational factors on radial clearance value let’s show external crescent chamber (\(V_{ext}\)) (between the outer wall of the orbiting scroll and the inner wall of the fixed scroll) and the internal chamber (\(V_{int}\)) (between the inner wall of the orbiting scroll and the outer wall of the fixed scroll). The suction volume of the external chamber is greater than the volume of the internal chamber.

The main factors influencing the radial clearance value are:
1. Accuracy of manufacturing. Scroll elements and the casing of a pump are made by milling in programmable controlled machine. Accuracy of manufacturing of eccentric driving shaft and bearing backlash influence the clearance value.
2. Force deformations. It is shown [3] that force deformations of scroll elements in scroll vacuum pumps are negligible owing to small gas loads. Local out-of-balance masses in a pump may result in deformation due to centrifugal forces but these forces are negligible.
3. Thermal deformations. Scroll elements in SVP are made from aluminum alloys with high thermal expansion coefficient. Complicated heat removal from the orbiting scroll and forced air cooling of the fixed scroll determine considerable temperature difference between them. These contribute to radial clearances alteration.

![Scroll vacuum pump SVP-12](image)

**Figure 1.** Scroll vacuum pump SVP-12: 1 – fixed scroll element; 2 – orbiting scroll element; 3 – anti-rotation mechanism; 4 – casing; 5 – driving shaft; 6 – counterbalance; 8, 9 – bearings; 10 – fan

2. **Thermal deformations calculation**

Thermal deformations of scroll elements may be described by equation $\Delta R = R\alpha(\Delta T)$, where $R$ is the distance from the shaft axis where the scroll is fixed (conventional scroll center) to arbitrary point on the scroll; $\alpha$ is the linear expansion coefficient; $\Delta T$ is the alteration of scroll element temperature in SVP operation. When materials with high heat conductivity coefficient are used then with sufficient for practice accuracy the elements temperature can be considered constant over the scroll thickness. Then the clearance alteration between the outer wall of the orbiting scroll and the inner wall of the fixed scroll may be calculated according to equation $\Delta \delta = R\alpha(\Delta T_s - \Delta T_k)$, where $\Delta T_s$ and $\Delta T_k$ are the temperature alterations of the fixed and the orbiting scroll in SVP operation, respectively. Therefore, the clearance between the outer wall of the orbiting scroll and the inner wall of the fixed scroll in SVP operation (its heating) decreases linearly from the scroll center to the periphery and increases linearly between the inner wall of the orbiting scroll and the outer wall of the fixed scroll.

The clearance value between the outer wall of the orbiting scroll and the inner wall of the fixed scroll should not be less than $R\alpha(\Delta T_s - \Delta T_k) + \delta_0$, where $\delta_0$ is the nominal clearance value which is necessary to prevent scrolls touching each other. The clearance value between the inner wall of the orbiting scroll and the outer wall of the fixed scroll should be sufficient to prevent scrolls contact at the beginning of SVP operation when scroll temperatures are equal.

For scroll compressors thermal deformations studies were carried out [4]. In [5] thermal deformations of single-sided and double-sided scroll elements of vacuum pumps were studied. Thermal fields of scroll elements were calculated in [6] by mathematical modeling and then thermal deformations were calculated with the help of finite element method in ANSYS Mechanical. As can be seen (figure 2) [5, 6] the radial clearance alteration over a scroll wrap angle has complicated character. Inlet pressure, operation conditions, shaft and anti-rotation mechanism design influence radial clearance value. The most clearances alteration is observed when double-sided scroll elements are used as the result of large dimensions, pumping speed and limited heat exchange conditions.
studied pumps the alteration of the radial clearance at the periphery of scrolls may reach 80 μm which greatly influences pumping characteristics when the nominal clearances are 100-120 μm. Owing to the higher temperature of the orbiting scroll element at the periphery the clearance for the external chamber decreases and for the internal chamber increases for the same value.

With the help of mathematical model based on the conservation equations [6, 7] calculations of the working process of the SVP-12 (figure 1) with nominal clearance of 105 μm at the worst cooling conditions and clearance alteration relative to the nominal clearance from 0 μm at the center to 80 μm at the periphery were carried out.

In figure 3 indicator diagrams for pump chambers with regard to clearance alteration due to thermal deformations and without them are presented. For the external working chamber owing to clearance decrease and backward leakage decrease at the periphery the less pressure at external wraps is observed. However, then, as the clearance increases, pressure increases and practically equals pump characteristics at constant clearance (without thermal deformations consideration). For the internal chamber the picture is contrary. Due to less scroll curvature radii backward leakage values will be more, and the pressure difference in chambers will increase, as well.

In figure 4 influence of clearance on pumping speed vs pressure relationship is presented. Operation of the pump with two working chambers with different suction volumes $V_{ext}$, $V_{int}$ and compression duration can be considered as parallel pumping by two pumps with different characteristics. At the beginning of pump operation at the same scroll temperatures the pumping characteristic is defined by
At high pressures at the pump inlet pumping speeds of each chamber will be summed up that is why the influence of clearance alteration due to thermal deformations is negligible in such conditions. With reaching the ultimate pressure in the lesser chamber and its further reduction owing to the operation of the greater chamber, the direction of total gas flow passing through the lesser chamber will change in the direction from the outlet to the inlet. Thus, the pump ultimate pressure is determined by the geometry of the lesser chamber. That is why the clearance increase in this chamber results in sharp decrease of the pumping speed at low pressures (line 3).

3. Deformations compensation
To compensate the clearance alteration at heating the presented design of orbiting scroll element is used (figure 5) where smooth increase of nominal clearance from the center to periphery is provided. This can be obtained by decrease of orbiting scroll basic circle radius in comparison with fixed scroll.

For modified scroll at ambient temperature clearance from the side of the external working chamber increases from the periphery to the center, and for the internal chamber decreases. Pump characteristic
is presented in figure 4 (line 4). In pump operation due to different heating of the orbiting and the fixed scroll elements the clearance becomes constant over the length of the scroll. This makes it possible to reach the greater pumping speed in the range of low pressures in comparison with the original design (figure 4 line 3).

4. Conclusion
This design makes it possible to decrease the nominal clearance, to provide the constancy of the clearance at pump working temperature and, thus, to improve the pump characteristics and to improve the reliability owing to decrease of scrolls touching probability. The design of the scroll pump with variable clearance is presented in [8].

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