THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE COOLING OF ROTARY ENGINES

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Summary

The flow pattern of heated rotary channels has an asymmetric spatial structure due to the combined effect of secondary flow generated by centrifugal and Coriolis forces, stabilization or destabilization near the suction and/or compression sides of the channel and of the entry swirl. Mathematical difficulties argue for determining the temperature field and heat transfer from test data. Four parameters have to be systematically varied in the measurements.

Increase of the power per unit volume of rotary engines — electromotors, gas turbines — entrails a rise of the operating temperature. On the other hand, operational safety requires temperature peaks not to exceed to value permitted by the mechanical and electrical strength. No economical construction fulfilling these two aspects simultaneously is possible but in the exact knowledge of the local temperature field.

A typical component of the cooling system of rotary engines, a longitudinal channel parallel to, and revolving around the axis at angular velocity $\vec{\Omega}$ with a radius R_0 is seen in Fig. 1. The cooling effect is due to a gaseous or liquid medium flowing in it, absorbing heat $\dot{q}$ per unit surface and unit time at the hot wall of the channel, heated by it from the original temperature T at a channel point with coordinates (r, φ, z). An exact knowledge of temperature field $T = T(r, \varphi, z)$ is needed for dimensioning the cooling system of engines since for, a given heat to be removed — that is, for a given heat flux $\dot{q}$ — the value $T(d/2, \varphi, z)$ of the channel wall temperature controls local temperatures of structural parts.

Provided a given velocity field $\vec{v}(r, \varphi, z)$ of relative motion existed in the channel (i.e. in knowledge of velocity components u, v, w vs. place), the temperature field would be easy to determine from the enthalpy balance of flow. Revolution induces, however, mechanical changes — themselves temperature-dependent — in the flow, compared to the well-known isothermal flow pattern in the channel at rest, that make the two fields to interact. Their determination requires to solve a second-order, nonlinear differential equation system consisting of the continuity equation, the balance of momentum and the balance of enthalpy under boundary conditions — a rather difficult problem [2], [3].

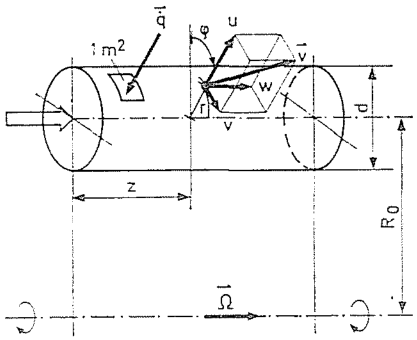

Fig. 1

Let us point out some factors causing the revolution to modify the flow mechanics processes in the channel at rest. Three of them are related to accessory forces arising in the rotating system — higher by orders than the gravity force — while the fourth concerns the history of flow entering the rotary channel.

Effect of centrifugal force

In a non-heated channel the flow is isothermal and the flowing medium is of practically constant density. In this case, centrifugal forces per unit mass $\vec{g}_\Omega$ arising in the rotating system modify though the pressure distribution in the plane of the channel cross section, but this has no effect on the flow pattern, as the centrifugal force pointing radially outwards, is balanced by the radially inwards force due to pressure at any point of the cross section. If, however, heat is supplied through the channel wall, the temperature becomes uneven in the cross section and the density distribution too: the flowing medium is cold and rather dense around the channel midline and warmer, thinner near the channel wall. The centrifugal field and an inhomogeneous density distribution, together may produce secondary flow in the cross-sectional plane normal to the flow. The relatively denser central core will move away from the axis of revolution, while continuity will be restored by warm layers near the wall tending towards the axis of revolution. Because of the symmetry of the generating cause, the secondary motion will be symmetric to the diametral plane crossing the axis of revolution, in a qualitative flow pattern seen in Fig. 2a.

Role of the Coriolis forces

The second accessory force interpreted in the rotating system — the Coriolis force $\vec{g}_C$ per unit mass — affects any mass element of the medium flowing in the channel at a relative velocity other than that parallel to the

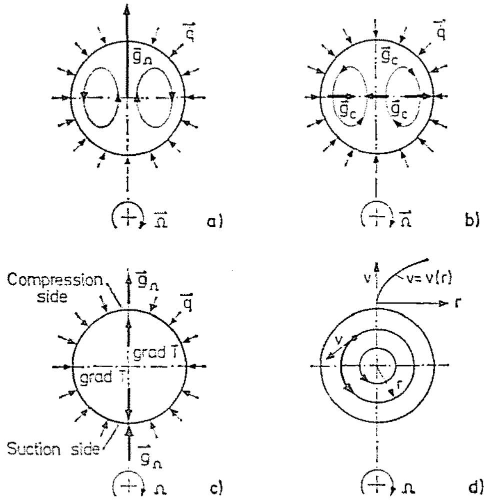

Fig. 2

axis of revolution. Direction of the effect is set out be vectorial product $\vec{v}\times\vec{\Omega}$ of relative velocity $\vec{v}$ by angular velocity $\vec{\Omega}$ of the system. Looking at the flow lines of the secondary flow due to centrifugal buoyancy in Figs 2a, and 2b, it is obvious that the channel cross section midparts near the diametral plane defined by the axis of rotation and the channel midline are subject to Coriolis forces opposite to, and in parts near the wall, in the direction of the revolution. Thereupon, the symmetry of the actual secondary flow ceases and the resultant is a complicated flow pattern in the cross-sectional plane. Analysis of the balance of momentum is likely to demonstrate the ability of the Coriolis forces to maintain secondary flow even in case of an isothermal flow because of their effect to modify pressure distribution over the cross section — as opposed to the centrifugal field (see e.g. [1], [2], [3]). This is, however, restricted to the entry region of the channel where the distribution of the axial velocity varies cross section-wise.

Stabilizing and destablizing effects

Vectors of the centrifugal field strength and the temperature gradient in two typical domains of the heated channel cross section have been plotted in Fig. 2c. Near the generatrix farther from the axis of revolution (a domain to be called briefly *the compression side* denoting that the hydrostatic pressure exceeds that in the channel midline, because of the centrifugal field) these vectors are of an identical sense or, at least include an acute angle, while near the generatrix nearer to the axis of revolution (in the *suction side*) they are of opposite sense, or include an obtuse angle producing a marked deviation between flow patterns developing on suction and compression sides. Let us imagine a low-density mass element to be driven by components normal to the wall of turbulent velocity fluctuations in the cross sectional plane toward the colder hence denser flow core. On the compression side, this mass element migration is opposite to, and in the suction side, the same direction as the centrifugal field. Local buoyancy resulting from the interaction of centrifugal field and density inhomogeneity during displacement of the mass element lighter than its surroundings works on the mass element on the compression side, adding to the kinetic energy of turbulent motion. (The analogon of this phenomenon is the accelerating rise of air masses warmer than their surroundings in the gravity field of the earth.) On the other hand, the displacing mass element has to work against buoyancy, hence its motion is to the detriment of turbulent kinetic energy. The same conclusion can be drawn for local processes near the compression and suction sides from the history of the relatively colder mass element getting from the flow core into the warmer environment near the wall. Accordingly, in heated channels, revolution acts as a stabilizer at the suction side, and as a destabilizer at the compression side; at the compression side, turbulent secondary motions are intensified, and at the suction side, they are weakened.

Entry swirl

Flow pattern in the entry region of the rotary channel depends highly on the velocity distribution of the flow reaching the entry cross section, dependent, in its turn, on widely varying geometries of pre-channel ducts and incorporated objects. This variegatedness of the flow history can be systematized from the aspect of the actual scope according to the entry swirl. Entry swirl is understood as the law of distribution $v = v\ (r)$ with respect to the place of tangential velocity components of specimens of the flow line family in the entry cross section seen in Fig. 2d. As a special case, the entry swirl may be understood as a rigid-body rotation relative to the channel, or even, as a swirl-free entry. (In the former case, $v(r)$ is a linear function, in the latter case, it identically vanishes.) Its role is that it is superposed on the secondary flow in the entry region of the channel, contributing thereby to the local heat transfer process.

The qualitative survey of typical factors in a rotary channel, aimed at stressing a fact of importance both for constructing engineers and for experimenter, namely that in a rotary channel, axial symmetry usual in the heat transfer process in channels at rest ceases and a temperature distribution intricately varying with local extreme values along the channel circumference has to be reckoned with.

Because of the mentioned difficulties of a theoretical analysis of this phenomenon, those experimenting are expected to submit reliable quantitative information to the construction engineer, to be obtained in systematic measurements. An analysis of the differential equation system showed in measurements with given flow conditions that at least four parameters have to be independently varied: mass flow; heat flux; rpm; and eccentricity, R_0/d. Measurements have to embrace the full range of parameters likely to occur in machine design practice.

References

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