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The structure of inertial flows in a fuel tank with guide baffles

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Abstract. *Purpose. Research of hydrodynamic mechanism of internal fuel flows in the spacecraft tanks with internal baffles for effective control.*
Methodology and approach. In the paper it is shown experimental and numerical simulation results of internal fuel flows in the spacecraft tanks with internal baffles, moving on the Earth's orbit. The structure of near wall flows - wall region, wake, around the baffle edges etc are shown. There are several cases that are shown for one, two and many vorticies or circulations around the baffles and outside of them, that characterize the energetic parameters of inertial flows in the tanks. The analysis of the structure and nature of circulating flows in the range of Reynolds numbers 700 ... 12500is presented, which allows to make a picture of axially symmetric circulation flow and rationally arrange the guide baffles in the inertial fuel flows. So, this provides to make a rational choise of effective facilities for compensating the disturbing influences on the tank walls by the fluid and substantial savings in spacecrafts long term flight at the Earth orbit.

Keywords: spacecraft tank; internal axisymmetric flow; circulating flow; guide baffle; Reynolds number; azimuthal velocity

Introduction

During the spacecraft flight on the Earth's orbit with the cut-off power engines the inertial effects of liquid fuel flows in reservoirs acts on its structure. They tend to cause instability of spacecraft motion and its deviation from the nominal trajectory, and can also be the cause of accidents on board. To compensate such disturbances, to correct fuel flow, to orient the object on its flight trajectory we must to switch periodically these engines, which leads to additional fuel consumption.

To improve efficiency on exposure to uncontrolled fluid flow in the internal fuel tanks stabilizing devices used in the form of annular and radial baffles on wall surface, which serve as guide vanes, but have a sufficiently large mass and size, thus reducing the payload of the spacecraft. Reducing the weight and the baffles area effect leads to a dramatic reduction measure effects on fluid and the need for more frequent switching control, so the problem arises of improving the efficiency of baffles influence on the flow of liquid fuel while reducing their weight, which can be solved by methods flows simulation in the laboratory and research hydrodynamic flow patterns in the tanks with baffles [1].

Research problem

The objective of this study is the experimental determination of the impact on a rigid radial walls on the flow of an incompressible viscous fluid in the reservoirs. Determination of the change rates when inertial rotation of liquid after the sudden stop in time the shell to determine the circular points are implemented by the inclusion of spacecraft engines automatic stabilization system [2].

The main criteria for evaluating impact on fluid flow represented well-known and specially designed numbers of similarity, for example, Reynolds, Rossby, Strouhal and others. Determination using them unsteady velocity distribution pattern directly about partitions and free space flow structure allows to set specific layers of a moving liquid in tanks with different variations. These parameters, in turn, can set the features of their influence on the inertial flow at different similarity numbers and extend the results of physical modeling of real structures and modes of objects movement. The main number of similarity seems centrifugal Reynolds number, built on the values of tank initial angular velocity Ω_0, the distance from the axis of rotation R and the fluid coefficient of kinematic viscosity ν

$$Re = \Omega_0 \bullet R_i / \nu.$$

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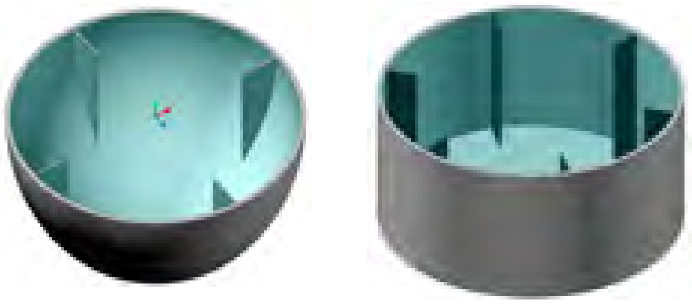

Fig.1. Internal radial near-wall baffles: a 4-cell, b - a 6-cell, in spherical and cylindrical tanks

As the basic construction of radial baffles taken adjacent to the tank inner side walls (fig. 2a), which are permanent devices in the spacecraft fuel tank [1, 2]. This makes it possible to adopt the measurements results of azimuthal velocity component obtained in the flows simulation in the special experimental stands [3, 4] when measuring velocity and pressure fields in comparison with measurements of other option structures.

Model testing of considered structures in spherical and cylindrical tanks carried out in the range of Reynolds Re_0 = 700 ... 12,500 and the Strouhal number Sh = 0 ... 32. When using standard designs on, shown in fig.2, but observed the initial pattern of distribution of layers axially symmetric flow. Zone 1 characterized quasi-solid flow region, which is not covered by baffles. This area seems to be quite stable, in which the initial velocity profiles are linear and independent of the distance from rotation axis.

Numerical simulation of flows under consideration involves the use of the full equations of motion of a viscous incompressible fluid in the form of the Navier-Stokes equations with the appropriate boundary conditions for the vanishing of the component of the velocity vector on the walls and on the axis of rotation of the model. In addition, to compare the hydrodynamic flow pattern held the calculations for unsteady flow problems when components of the fluid velocity vector fade from solid distribution rate to zero.

For small values of the angular velocity of the flow corresponding to the Reynolds number of about 700 ... 2500 centrifugal forces of inertia and Coriolis forces are quite small, so the test calculations in the finite element scheme more appropriate to hold for two-dimensional problems with an infinite radius of surface curvature. First, it will reduce the duration of the calculations and allow to split the space into a grid with an arbitrary number of finite elements. Second, it will provide a qualitative determination of the hydrodynamic flow and distribution of flow basic kinematic and power parameters.

The analysis of experimental and numerical results

Analyzing the results of velocity field measurement, shown in fig.2, it can be established that the size of the intermediate zone, typically up to standard size R = 0,73 ... 0,8, it is adjacent to the baffle inner edges and serves as the transition area between zone 1 and the wake after the baffle (zone 3). In this area, there is a diffusion of internal borders baffle wake and distribution of circulation in the axis direction, initiated by baffle inner edges. As you can set the width of the baffle influence zone 2, zone 1 in the quasi-solid.

The most characteristic for axisymmetric flow seems to zone 3, indicating the wake of the baffle plane. This layer flow is strongly influenced by the septum and on its size and characteristics of the velocity field formation depends on effective influence on. Furthermore, the width of this area flow strongly influence the near-wall flow (zone 4). Analysis of numerical simulation results and flow structure near the baffle provided the approach to the flows numerical simulation in tanks. There is the first determination of criterial parameters, i.e., Reynolds number, Rossby number, etc. To ensure the necessary reliability of numerical calculations results are repeated at constant input values in dimensionless form at Re = 700 ... 12,500.

Fig. 2. Typical flow zone in cylinder with continuous baffles: a - adjacent; b - spaced 1 - quasi-solid region; 2 - the transition zone; 3 – eddy wake behind the baffle; 4 – boundary layer

It is known that a decrease in wake size reduces the frontal walls of resistance. As a basic accepted baffle width b = 0,2 • R, adjacent to the tank walls [4]. A more detailed evaluation of the wake structure behind the adjacent wall, a schematic representation of which is shown in fig.3, the characteristic size of the circulation areas: the partition length l and the width b_1, and b_2 the width of the inner edge of the baffle effect on space flow [5] .

It was found that at low flow rates (Re = 670 ... 1020) length of the wake can be 1,4 ... 1,92 • b, and its width - 1,1 ... 1,18 • b. The width of baffle influence area to uncovered her space, can be b_2 = 0,35 ... 0,57 • b. Increasing the Reynolds number Re = 1020 ... 1720 leads to an increase in track length, b = 2.5 ... 3.1, while its width is slightly increased, total 5 ... 8%. For impact area width b_2 characterized by the following relation b_2 = 0.31...0.43 • b, indicating the stabilization effect on the flow baffle in general.

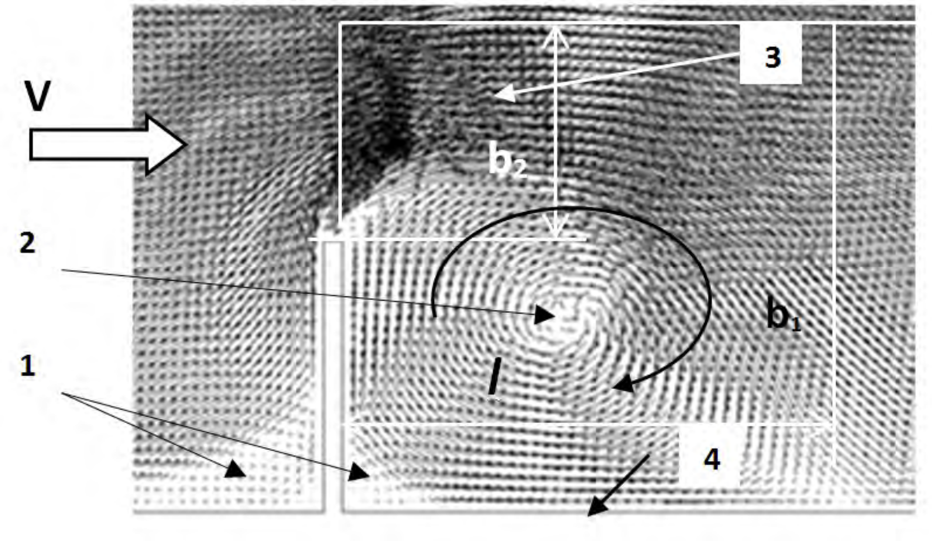

Fig. 3. The flow structure in vicinity of the adjacent solid baffles (width b_0 / R_0 = 0,2) when Re = 920: 1-stagnant zones;2 - circuit; 3 - area of influence on the baffle edge for quasi-solid; 4- tank wall

In the flows simulation in view of axial symmetry problem is necessary to check the correctness of the boundary and initial conditions of the model based on the Navier-Stokes equations. For this test examined baffle flow problem in tanks with an infinitely large radius of curvature, calculating the results of which are shown in fig.4 [6, 7]. For example, at a flow of 6-cell (fig.4,a) and 8-cell (2b), where the walls are located at a distance $l = l_0 / R_0$ = 0,73 ... 1,0, sizes wake of the first partition significantly exceed the distance over which the second bulkhead spaced from the first so it can only take part of the dynamic pressure of the flow. Thus, the efficiency of cascade baffles is reduced, and to improve its barrier effect should be moved beyond the wake. The distance between the baffles should be set to l_1, which under these Reynolds numbers commensurate circulation wake.

For an 8-cell baffle (2b) flow pattern becomes even more irrational, as formed during steady braked with velocities of the order of 0.01 in the vicinity of walls 0,025 •b, which has a very low impact on other areas of the course. Each of the baffle initiates increase in velocity near the inner edge, which quickly decay (ΔT = 2.9...3.7), not having a noticeable effect on the quasi-solid flow region.

When using the 4-cell design on the calculation results are shown in fig.4,b, there is a leveling of circulation size and distance between the elements, so in terms of the circulation formation design on it is more effective. Furthermore, its impact on the quasi-solid flow region becomes more significant, increasing the flow rate of about baffles edge on 12...17%, indicating a corresponding reduction in the flow space not covered by baffles [6].

At the same velocity in the gaps between the outer edge and the tank wall increases, the circulation in the baffles wake are deformed toward the quasi-solid flow region, thus making a significant contribution to the azimuthal velocity profile in the headspace of the flow. In turn, the impact of this gap on the dependence of the circular highlights the dynamic fluid effects on the plane baffles appears as significant as in the initial moments of the passage of time there is the effect of "slippage" of the fluid in the wall region, which reduces peak force on the baffles [7].

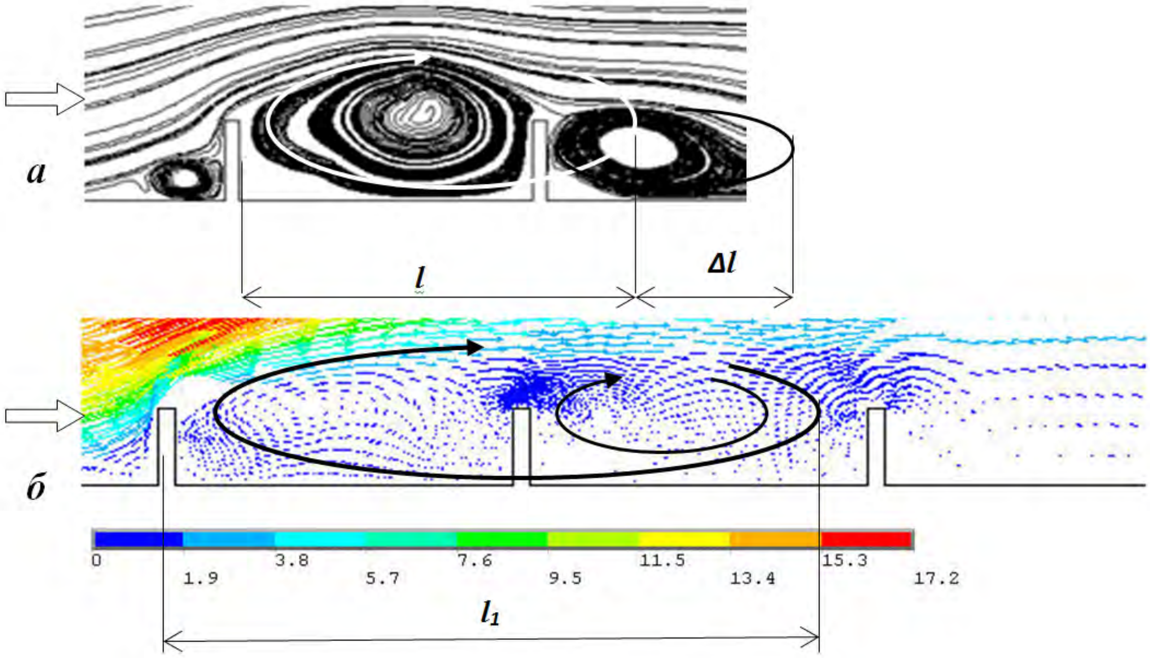

Fig. 4. Contour image circulation in the wake for continuous adjacent baffles at Re_0 = 920: and - 6-cell; b - 8-cell

Thus, in the considered range of Reynolds numbers flow structure essentially depends on the width of the baffles, the number and their location relative to the tank walls. This allows to vary the influence on inertia within and thus accurately determine the value of disturbance compensation effects on the liquid side.

Conclusions

The analysis results of this study revealed that in the range of Reynolds numbers of 700...12500 in spherical tanks of spacecraft might be axisymmetric laminar flow of liquid fuel, the presence of stable circulation, which creates resentment and dynamic loads on the wall. Determination of hydrodynamic fields in these flows allows you to set the structure of flows in specific areas in the vicinity of baffles in the wake, the wall region and on the edges of the walls.

On the basis of the results obtained, the distribution characteristics and flow circulation structure in the specific areas of the tank with baffles can set the minimum number of baffles, their width and location near the walls of the most effective influence on the flow. By the nature of the wakes formation and flow at the baffle edges can be to establish the effect of baffles on the quasi-solid flow in area not covered by baffles and thus more accurately determine the nature of the baffles effect within the whole.

Comparison of experimental data on quasi-solid flow region allows us to conclude a strong influence on its walls, in which the decay rate is much faster than, for example, spaced solid construction. Analysis of numerical simulation results allowed to clarify the qualitative picture of the flow in the vicinity of the baffles and indicates sufficient complexity hydrodynamic fields in the flow of a viscous incompressible fluid. This, in turn, must be considered when drawing up the nomogram force effects, which is introduced into the on-board spacecraft computer stabilization system for optimization of compensatory measures during its orbital flight.

Структура инерционных течений в топливном резервуаре с направляющими аппаратами

В.А. Ковалев

Аннотация. *Цель. Исследование гидродинамического механизма внутренних течений топлива в баках космических аппаратов с внутренними направляющими аппаратами для эффективного управления жидкостью.*

Методология и подход. В статье представлены результаты экспериментального и численного моделирования внутренних течений топлива в баках космических аппаратов с внутренними перегородками, движущихся по орбите Земли. Показана *структура пристенных течений - область стенки, спутный след, окрестности кромок перегородки и т. д. Представлены несколько случаев существования одного, двух и нескольких вихрей или циркуляций вокруг перегородок и в свободном пространстве резервуара, которые характеризуют энергетические параметры инерционных потоков. Приведен анализ структуры и гидродинамический механизм циркуляций в диапазоне чисел Рейнольдса 700 ... 12500, позволяющий представить картину осесимметричного инерционного течения и рационально расположить направляющие аппараты в потоке. Таким образом, это позволяет рационально выбирать эффективные средства для компенсации возмущающих воздействий на стенки резервуара жидкостью и существенно сократить затраты топлива при длительном полете космических аппаратов на околоземной орбите.*

Ключевые слова: резервуар космического корабля; внутреннее осесимметричное течение; циркуляция; направляющая перегородка; число Рейнольдса; азимутальная скорость

Структура інерційних течій у паливному резервуарі з напрямними апаратами

В.А. Ковальов

Анотація. *Мета. Дослідження гідродинамічного механізму внутрішніх течій палива в баках космічних апаратів з внутрішніми напрямними апаратами для ефективного управління рідиною.*
Методологія і підхід. У статті представлено результати експериментального та чисельного моделювання внутрішніх течій палива в резервуарах космічних апаратів з внутрішніми перегородками, що рухаються орбітою Землі. Показана структура пристінних течій - область стінки, спутний слід, околиці крайок перегородки і т. Д. Представлені кілька випадків існування одного, двох і декількох вихорів або циркуляцій навколо перегородок і у вільному просторі резервуара, які характеризують енергетичні параметри інерційних потоків. Наведено аналіз структури і гідродинамічний механізм циркуляцій у діапазоні чисел Рейнольдса 700...12500, що дозволяє уявити картину осесимметричноъ інерційноъ течії і раціонально розташувати напрямні апарати в потоці. Таким чином, це дозволяє раціонально вибирати ефективні засоби для компенсації збурюючих впливів на стінки резервуара рідиною та істотно скоротити витрати палива при тривалому польоті космічних апаратів на навколоземній орбіті.

Ключові слова: резервуар космічного корабля; внутрішня осесиметрична течыя; циркуляція; напрямна перегородка; число Рейнольдса; азимутальна швидкість

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