CONTROLLED BOUNDARY LAYER ON THE SOLID WALLS OF WIND TUNNELS: NEW APPROACH TO THE BOUNDARY INTERFERENCE PROBLEM

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Abstract

A new approach to the boundary interference problem for subsonic and transonic wind tunnel is developed based on the idea of using controlled boundary layer on the test section walls. The results of tests in TsAGI T-112 wind tunnel show that the new approach allows effectively reduce the boundary interference.

1 Introduction

Wall interference effect remains one of the most important factors distorting the wind tunnel test results, especially for transonic flow regimes. Traditionally the wall influence is taken into account by means of the boundary interference corrections applied to the balance test data. Dependent on the used calculation method, corrections may be applied either to differential characteristics (e.g. pressure distribution) or integral parameters (typically, Mach number and the angle of attack). The last approach is used when the flow disturbances are not very intensive and the flow field around a model in the test section is similar to that in the infinite flow but at slightly different flow conditions. In the case when the interference is strong the flow over a model may not be realized in the infinite flow at any combination of its characteristics and the correctness of the boundary interference approach should be checked individually for each test. This problem is the most acute at transonic velocities, because the non-linear effects accompanying the local supersonic zones and the shock waves appearance make problematic the application of most of the traditional boundary correction methods.

The second approach is the so-called “adaptive-wall wind tunnels”. This concept implies that the boundary conditions during the test may be changed in such a way that the wall interference will be removed or at least considerably diminished [1- 3].

The adaptive-wall concept is based on the well-known characteristic: distribution of the normal velocity component on the incompressible flow boundary fully defines the flow field inside it. Consequently, if the normal velocity distribution over the near-wall control surface becomes the same, as in the infinite flow, the wall interference will be eliminated.

Practical implementation of this idea encounters a set of difficulties. First of all, it is difficult to predict precisely the normal velocity component distribution in the total transonic velocity range where interference is maximal. The iteration procedure of Sears [3] seems to be the most relevant for this case. One of the parameters (e.g. tangential velocity component u) serves as a boundary condition for calculation of the virtual external flow field. The result of this calculation is the definition of the second parameter (in this case – the normal velocity component v). Comparison of the calculated and measured distributions of v serves as the criterion of proximity of the boundary conditions to the interference-free ones.

The advantage of such approach is the relative simplicity of the far field calculation, free from any viscous transonic effects prediction near the model surface and using the turbulence models.

In the wind tunnel with the sectioned gas injection and suction the necessary v-distribution is realized by means of forced convection through the permeable wind tunnel wall sections. Theoretical and CFD surveys of this kind of adaptive boundaries [1] demonstrate principal inability to eliminate the perforated-wall interference at constant pressure in the unique plenum chamber surrounding the test section. At the same time even minimal sectioning of the plenum chamber allows for significant decrease of wall interference.

In the wind tunnels with ventilated-wall test sections desirable values of the normal velocity components are achieved using the control of the open-area ratios of perforated or slotted walls. The unique experience achieved during the exploitation of TsAGI T-128 wind tunnel with ventilated test sections demonstrated significant success in realization of low-interference test technique, [4]. Multi-sectional walls with individually-controlled perforated panels gave an opportunity to apply the Sears' scheme for realization of the adaptive-wall technique, [5]. However, due to abovementioned principal restrictions, interference of the perforated walls can't be removed totally in the case of one plenum chamber with constant pressure. Calculations [6] show that variations of the plenum pressure enable to minimize the lengths of the zones where interference-free boundary conditions are impossible.

One more type of the adaptive-wall wind tunnels is the self-streamlining facilities, having flexible walls of the test sections. Interference-free conditions are achieved in these wind tunnels when, as a result of the iterative procedure, the wall shapes correspond to the infinite-flow streamlines. Iterations include calculations of external flow inside the test section and the wall boundary layer. This approach is usually applied only for the 2D models tests.

Application of all adaptive-wall technologies is very expensive, requiring a lot of time and other resources. Due to complexity and some restrictions these approaches are rarely used in industrial wind tunnels. To find the solution to the boundary interference problem it is necessary to look for new ideas which may be implemented in the standard wind tunnel tests.

2 Work Statement

Actively operating transonic wind tunnels usually have ventilated (perforated or slotted) walls, some of them having an opportunity to change the open-area ratio of the walls. Common test technique for perforated-wall facility includes the choice of optimal open-area ratio (made a-priori) and introduction of the wall interference corrections to the model testing characteristics after runs, which take into account the residual wall influence. Although this approach proved to be rather effective [4], it contains inevitable drawbacks, associated with the boundary conditions themselves. Linearized boundary conditions for perforated walls are usually written as linear relation between two components of the "disturbed" velocity (the so-called Darcy-type boundary conditions):

$$u + \frac{v}{R} = 0 \tag{1}$$

where u and v are non-dimensional disturbed velocity components, and R is the permeability factor, equal to 0 for solid wall and ∞ for free boundary. As it was demonstrated for the 2D infinite flow (see, e.g. [7]), elementary singularities produce disturbances on the control surface, parallel to the x-axis, shown in Fig.1. If parameters on the real flow boundary replacing the control surface are the same, the flow inside these boundaries will be interference-free for given singularities.

For all three cases curves for velocity components u and v have different types of symmetry with respect to the axis x=0. It means that Darcy-type boundary condition (1) can't be satisfied for significant parts of boundaries where u and v have the same sign. As a result, perforated walls can't remove simultaneously both the interference upwash (downwash) and its gradient at any chosen permeability. It means that either lift coefficient or pitching moment coefficient behavior will be inevitably affected by the boundary interference.

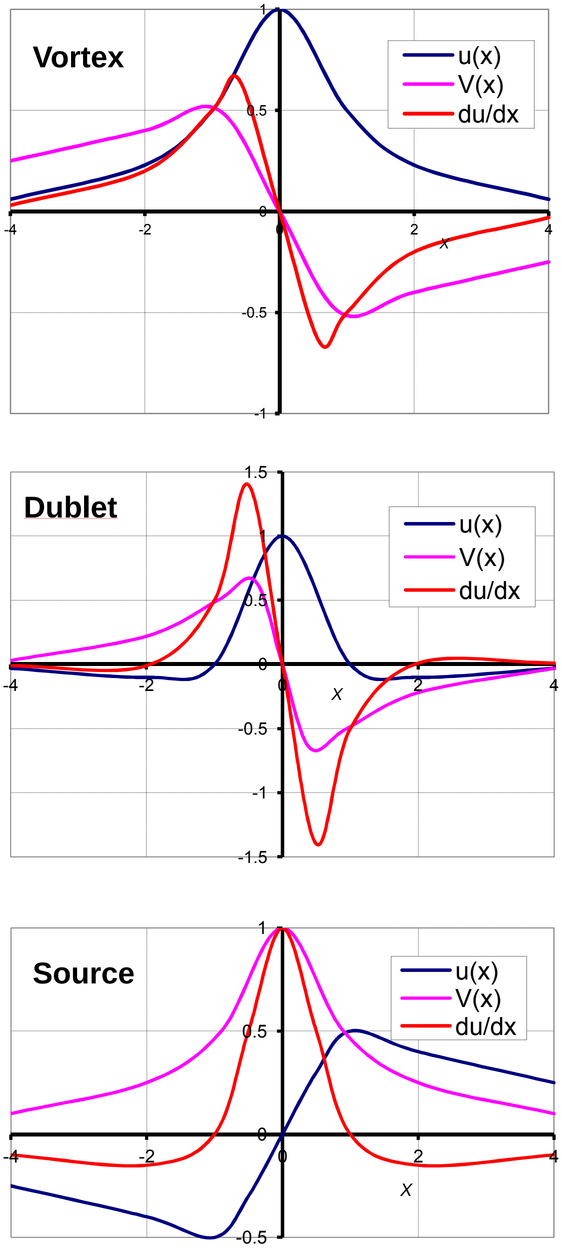

Fig.1. 2D disturbed flow parameters on the control surface in the infinite flow for elementary singularities, [7].

An alternative approach to the boundary interference problem was proposed by V.M. Neyland and V.Ya. Neyland, [8]. The so-called “jet boundaries” formed by the near-wall jets parallel to the test section walls demonstrate some unique characteristics. Their interaction with the model-induced disturbances depend on the relative jet thickness and the jet/main flow dynamic pressure ratio. Variation of this ratio from infinity to zero changes the boundary property in the range from the solid wall ($v \equiv 0$) to the free boundary ($u \equiv 0$) ones, which is similar to the perforated wall with the changeable open-area ratio. But in the linearized form the conditions on the jet boundary may be presented as follows [7]:

— (2)

Proper choice of γ-factor in the jet boundary condition (2) allows obtain the coincidence of the v and amplitudes in the zone of highest disturbances, Fig.1. The more organic nature of jet boundaries may be illustrated by the fact that infinite flow may be also considered as the limit case of flow in jet boundaries with infinitely thick jets and the dynamic pressure ratio equal to 1. V.M. Neyland [7] showed the algorithm of jets optimization resulting in practical removal of the wall influence. The residual interference appeared to be significantly lower than that for optimal perforation in the approximately similar conditions. Besides the main preference, jet boundary may have some more useful properties, such as lower noise level compared to perforated walls, possibility of the thermal insulation of the cryogenic flow, etc.

Although the jet walls effectiveness was demonstrated both theoretically and in the small pilot facility conditions, this approach was not yet widely implemented. One of the reasons is the technological difficulty of the controlled jets arrangement in the industrial wind tunnels. The purpose of this work was to develop a new approach based on the jet boundary concept but not demanding complicated technical solutions. We proposed to use the controlled boundary layer on the solid test section walls as the jet boundary analogue, because boundary layer may be considered as the near-wall jet with lower (compared with the main flow) dynamic pressure. This choice seems correct because, according to the conclusions [7], the optimum jet near the solid wall should always have lower dynamic pressure than the main flow.

3 Test Facility and Test Technique

The purpose of the first test campaign was to demonstrate the effectiveness and the possibility of practical realization of the proposed approach. Test facility chosen for these experiments was the trisonic TsAGI T-112 wind tunnel that was previously often used for solution of the test technique problems and as a pilot facility for the new concepts implementation. Main technical characteristics of T-112 wind tunnel are the following:

Mach number range	0.6…1.2, 1.5, 1.77
Reynolds number	up to $15\cdot10^6$
Total pressure	Atmospheric
Dynamic pressure	up to 45 KPa
Total temperature	300 К
Standard run duration	300 s
Test section size	0.6×0.6×2.59 m
Model pitching angle range	-4º…+24º

T-112 is a semi-closed circuit, ejector-type facility. Standard tests are performed either in perforated walls (with 2-size or 4-size perforation) or in solid walls. Solid walls are used mainly for the supersonic tests at M=1.77. The open-area ratio of the horizontal perforated walls is 23%. Vertical perforated walls (if they are installed) have the 15% perforation. In the range from M=0.6 to 1.2 the flow velocity is changed continuously; for these regimes the subsonic nozzle is used. Regimes M=1.5 and 1.77 are obtained using supersonic nozzles. The wind tunnel is equipped with the 4-component mechanical balance and a set of strain-gage balances for different kinds of models tested.

Boundary layer control on the top and bottom wall was realized with the help of the wedge-formed spoiler grids mounted at the test section entrance and aimed at creating the additional drag in the near-wall region, Fig.2. The spoiler height might be changed manually from 0 to 32 mm. In the model location zone the boundary layer parameters were measured using the Pitot tubes rake (Fig.3). Boundary layer characteristics were changed in wide range. In particular, the displacement thickness varied from 6 mm to 36 mm, i.e. from 2% to 12% of the test section half-height.

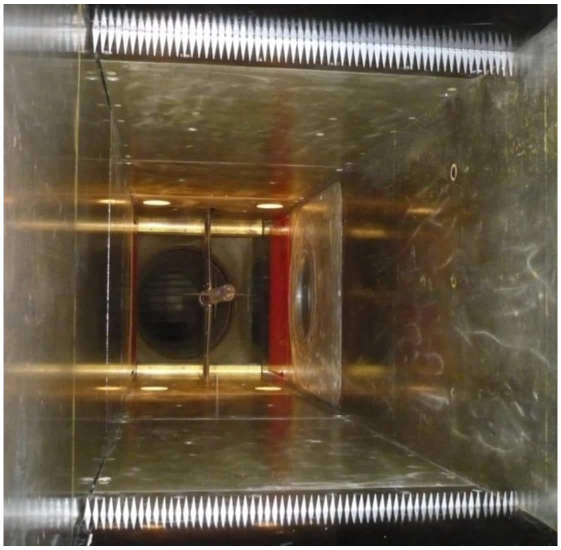

Fig.2 Spoilers at the test section entrance, T-112 wind tunnel

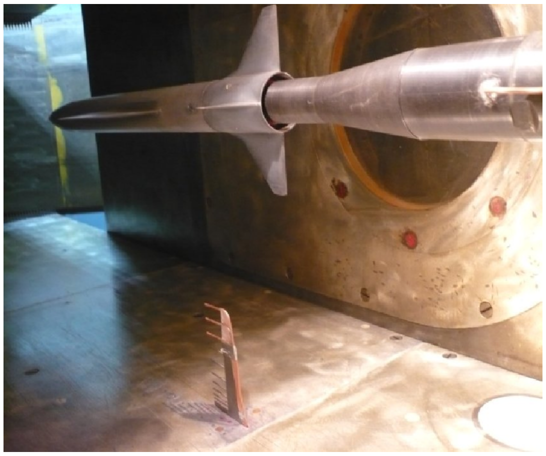

Fig.3 Reference model 12299-2 and boundary layer rake in T-112

In the first experiments the standard reference model 12299-2 was tested at Mach number 0.6 and 0.8 in different boundaries: in solid walls, in the 2-side perforation and in solid walls with the controlled boundary layer on the horizontal walls. The reference model itself represents the cylindrical body with triangle wing and cruciform empennage, Fig.3. The second test series included tests of 3 geometrically-similar models of the same type. Testing of the geometrically-similar models is the well-known way to estimate the boundary interference. It is considered that the proper choice of boundaries can lead to coincidence of the aerodynamic characteristics for all such models. Although this method is debatable, it helps when there is no more reliable criterion, such as, e.g., the infinite-flow results. Models are shown in Fig. 4, and their dimensions are given in Table 1.

Fig.4. Three geometrically-similar reference models.

Model	Wing area [m^2]	Model length[m]	MAC[m]
12299-1	0,03	0,5098	0,188
12299-2	0,048	0,6445	0,238
12299-3	0,062	0,7322	0,270

Table 1. Reference models dimensions.

All three models were tested in the same conditions at Mach numbers 0.6 and 0.8 and angles of attack from -4˚ to +16˚. For these tests only three positions of spoilers (0, 20 and 32 mm) were chosen.

4 Experimental Results

$C_L(\alpha)$ curves obtained in the first test series are shown in Fig.5. It is very important, that application of the spoilers enabled to obtain wide range of curves, the first of which being the solid-wall $C_L(\alpha)$ characteristic, and the last (for the 30 mm spoiler height) practically coinciding with the 23% perforated-wall curve. Since the 23% open-area ratio is considered to be the surplus one and exceeds the supposed optimal value, our results demonstrate the possibility to cover all range of characteristics for perforated-wall configuration, including the optimal one, which should be the closest to the infinite-flow curve.

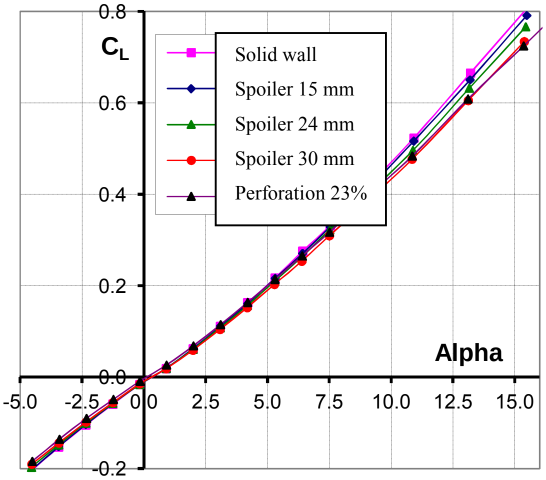

Fig.5 $C_L(\alpha)$ curves for different boundary conditions. M=0.8.

In the second test series along with the models aerodynamic characteristics the boundary layer velocity profiles were measured on the horizontal wall near the model. Typical boundary layer profiles *(Y)* for three spoiler positions are shown in Fig.6.

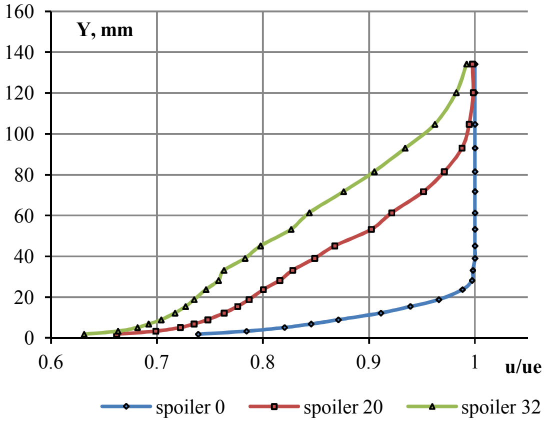

Fig.6. Velocity profiles in the boundary layer.

The average calculated values of the boundary layer displacement thickness δ^* and momentum thickness δ^{**} (or θ) are given in Table 2.

Spoiler height, mm	*δ*, mm*	*δ**(θ), mm*
0	5,43	2,81
20	21,07	12,41
32	33,01	19,39

Table 2. Integral boundary layer characteristics.

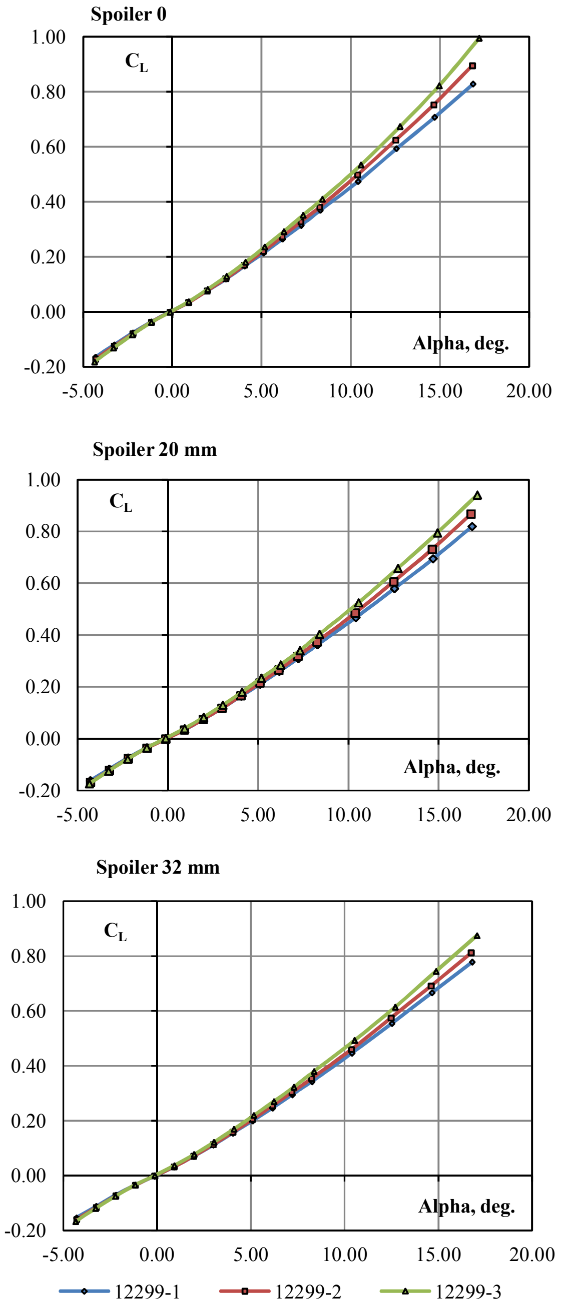

Fig.7. $C_L(\alpha)$ curves for three models at different spoiler heights. M=0.8,

Data analysis confirms that controlled boundary layer technique permits to improve the agreement between the characteristics. $C_L(\alpha)$ curves for three models at different spoiler heights (Fig.7) demonstrate that better results were obtained for 2 smaller models. Concerning the large model 12299-3, it was evidently oversized for this wind tunnel and the applied boundary layer had not enough thickness to compensate the solid wall effect.

Similar results were obtained also for other main aerodynamic characteristics. The pitching moment curves also demonstrate substantially better agreement in the presence of thick boundary layer on the top and bottom walls.

The first results analysis allows expect that application of the controlled boundary layer in combination with the solid (and maybe also porous) walls of the test sections may become a simple and rather effective method of eliminating the boundary interference in subsonic and transonic wind tunnels.

5 Model characteristics in the infinite flow

The only real confirmation of the boundary interference approach correctness is direct comparison of the results obtained in the wind tunnel with the model characteristics in the infinite flow. These “infinite-flow” characteristics may be obtained in the wind tunnel with larger dimensions, as it was done in [4], when T-128 results for the transonic reference model (blockage 0.37%) were verified in the AEDC 16T facility (blockage 0.07%). In the case of models with relatively simple geometry the infinite-flow characteristics may be also obtained numerically. In this work we suppose to calculate these reference characteristics using ANSYS CFX code. The first encouraging results were obtained for the solid-wall conditions on the 9 million cells mesh with the $Y+$ in the near-wall region of the order of 0.5, Fig.8. The turbulence model SST with the Gamma-Theta model of turbulence transport was used for correct definition of the laminar-turbulent transition location. The CFD results are in rather good agreement with the test data, Fig.9. Further work on the infinite flow modelling over a model is planned for the near future.

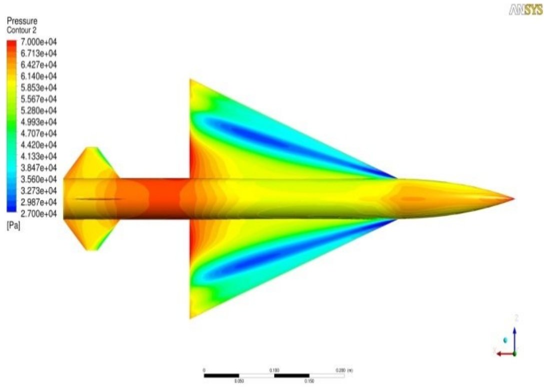

Fig.8. Pressure distribution on the model surface at M=0.8 and α=16˚in solid walls.

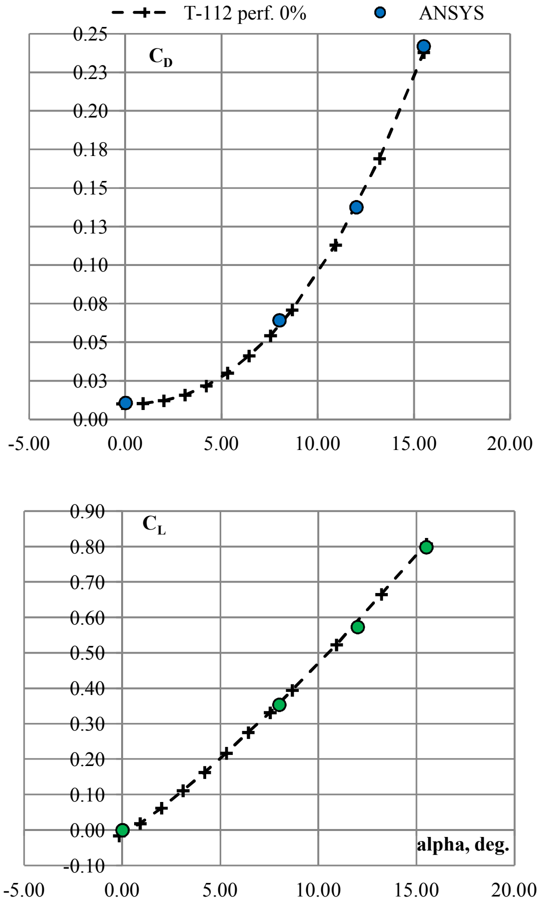

Fig.9. Comparison of experimental and predicted $C_D(\alpha)$ and $C_L(\alpha)$ curves, M=0.8, solid walls.

6 Conclusion

As a result of the present analysis, it may be concluded that traditional methods of the boundary interference decrease basing on the ventilated walls application have some fundamental restrictions mentioned above. Jet boundaries permit to eliminate practically the wall influence on the model characteristics, but their technical realization is rather complex.

The controlled boundary layer concept may be considered as a simpler but rather effective variant of jet boundaries. The first test series in T-112 wind tunnel gave the encouraging results, demonstrating the model characteristics variation in wide range, presumably including the optimal (close to the infinite-flow) curves. The next step of investigations will imply obtaining of the reference infinite-flow model characteristics by both the experimental and the CFD-methods.

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