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CAD and CAE Analysis for Siphon Jet Toilet

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Abstract

The high precision 3D laser scanner with the dual CCD technology was used to measure the original design sample of a siphon jet toilet. The digital toilet model was constructed from the cloud data measured with the curve and surface fitting technology and the CAD/CAE systems. The Realizable $k-\varepsilon$ double equation model of the turbulence viscosity coefficient method and the VOF multiphase flow model were used to simulate the flushing flow in the toilet digital model. Through simulating and analyzing the distribution of the flushing flow's total pressure, the flow speed at the toilet-basin surface and the siphoning bent tube, the toilet performance can be evaluated efficiently and conveniently. The method of “establishing digital model, flushing flow simulating, performances evaluating, function shape modifying” would provide a high efficiency approach to develop new water-saving toilets.

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1. Introduction

Traditionally, the development process of the high performance toilet was manually operated by the master craftsman by the way of many trials. This method needed long development period, rich expenses and more difficulties for developing new water-saving products. With the advance of optical measuring and digital manufacturing technologies, it has become possible to utilize this advance efficiency method to develop new type water-saving toilet. For investigating the digital integrated manufacturing solutions, the simulation of toilet flushing flow process play a very important part, which can analyze and improve the flushing performance of the toilet's digital prototype in the computer before the trial manufacture. This method can evaluate the toilet's performance quickly and make the new water-saving product developing conveniently [1]. In this paper, the cloud data of the toilet digital model were measured by scanning a toilet's developing sample with the 3D scanning measurement technology using the line laser sources and dual CCD acquisitions. The 3D toilet digital model was built with the CAD/CAE including edge detection, filtering, curve and surface reconstruction according the cloud data of it. The method to simulate the toilet's flushing flow processes and to evaluate the toilet's performance were proposed and

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researched. With this “establishing digital model, flushing flow simulating, performances evaluating, function shape modifying” method, the best performance toilet type would be developed rapidly.

2. Toilet Digital Model Construction

The digital toilet model was constructed by the curve and surface fitting from the measured data. Measured by the 3D laser scanner with the dual CCD technology, the cloud data (a large number of point data) of the original toilet sample were obtained. The measured point data were preprocessed by noise filtering, point data smoothing, point data filtering and so on. Then the curves and surfaces of the toilet have been built and edited as well as the curve curvature and surface errors have been analyzed. After the preprocess, the curve and surface data of the toilet have been transferred to the CAD/CAE systems through the conversion interface such as IGES, and those data have been put together according the inter-relationship among the alignment of the coordinate system and the wireframe alignments to establish toilet wireframe model with the assisted analysis software. The completed digital model for the original toilet sample was shown as Fig.1.

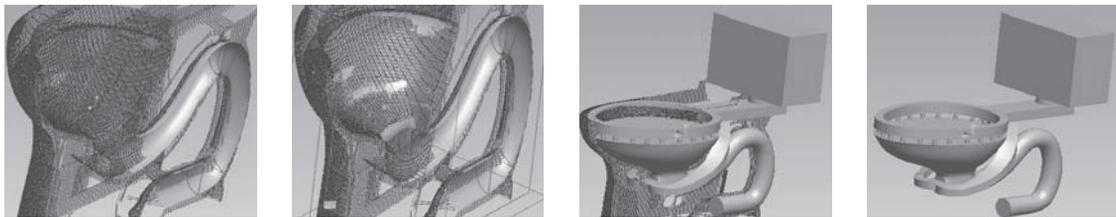


Fig. 1 Toilet digital model

3. Principle of Toilet’s Flushing Flow Simulation

The simulation of the toilet’s flushing process has been mad with the finite element analysis software and the toilet digital model. The flushing process of the siphon jet toilet is a complicated multiphase flow problem with the three-dimensional unsteady states and the free surface boundary conditions. Those problems can be simulated with the pressure solver in the FLUENT software package based on the low speed and incompressible flow. The flushing flow model, wall surface conditions and the calculating models used in the simulation were in what follows.

The Realizable $k-\varepsilon$ double equation model of the turbulence viscosity coefficient method was used as the flush flow model for the numerical simulation [2]. Realizable model is the complement of the standard $k-\varepsilon$ model and the RNG $k-\varepsilon$ model. The “Realizable” means that the model satisfies certain mathematical constraints as same as the turbulence flow model. The transport equations of the Realizable $k-\varepsilon$ double equation model are as follows:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\alpha_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (1)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\alpha_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S_\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \quad (2)$$

$$C_1 = \max \left[0.43, \frac{\eta}{\eta + 5} \right], \quad \eta = S \frac{k}{\varepsilon}$$

Where k equation is same as the k equation in the standard $k-\varepsilon$ model and the RNG $k-\varepsilon$ model except the constants, but the ε equation is quite different as which in the standard $k-\varepsilon$ model and the RNG $k-\varepsilon$ model.

The standard $k-\varepsilon$ model is appropriate to simulate the general turbulence. RNG $k-\varepsilon$ model is generally used to treat the flow which has high strain rates and larger degree of bending streamline. Realizable $k-\varepsilon$ model has some advantages in simulating the flows such as mixed jet stream flow, pipe flow, boundary layer flow and separation flow. All of these models above are belong to the high Reynolds number model and suitable for the turbulence flows which have developed very adequately in the region having some enough distance to the wall surface. In the region nearby the wall surface, the molecular viscosity in the flow could have some strong influence than the

turbulence fluctuation influence and would produce the turbulence developed insufficiently, which would lead to make the flow being in a laminar flow state in this region. So the semi-empirical formula was used directly to link the physical solution variables on the wall surface with the variables where in the core area of the turbulence. Therefore the core region of the flushing flow should be simulated with the Realizable $k-\varepsilon$ model and the flow in the edge range nearby the wall surface should be treated with the semi-empirical formula which directly links the physical solution variables in the wall surface with the variables in the core area of turbulence. That's the value of the variable nodes in the wall nearby range could be directly equal to the adjacent control volume of the wall surface, and the first inner node in the wall nearby range had been put on the logarithmic region and configured to enough developed turbulent region.

Flushing flow of the siphon jet toilet belongs to the fluid flow problem with free surface whose shape and location would vary intricately and continually. Such problems could be simulated with the VOF multiphase flow model very well. In the VOF model, the fixed Eulerian's grids were used to track the multiphase flow surfaces and the different fluid components sharing a set of momentum equations, and the volume ratio occupied by every fluid composition of each grid unit could be calculated [3]. All variables and their property domains were shared by each phase flow unit and represented the volume-averaged values. The volume ratio of each phase at whatever location has been calculated. Each flow unit's variables and their attributes were simply belonging to a phase or a phase mixture, absolutely depending on the volume ratio value. Thus if the q -phase fluid volume ratio was denoted by α_q in an unit, and the three following conditions were possible:

- (1) $\alpha_q = 0$, When the q -phase fluid in the unit was empty
- (2) $\alpha_q = 1$, When the q -phase fluid in the unit was filled
- (3) $0 < \alpha_q < 1$, When the unit contained the q -phase fluid and another phase or multiphase fluid interface

According to the local values of α_q , the appropriate properties and variables were assigned to each control volume in a certain range. Through solving a phase or multi-phase with the volume ratio of the continuity equation, the interface of tracking phase could be obtained.

The model of three-dimension non-steady fluid was used for numerical calculating; the flushing flow speed was looked as the absolute speed; the unit pressure gradient was used for the derivative item of control equation. The time-related items were calculated using one-order implicit expression. The reference point was adopted on the top of water tank where was full of air. The dimensional coordinate was (356, 574, -170) and the acceleration of gravity was -9.81m/s^2 . The lightest air phase density was selected for work density, which would eliminate the accumulation effect of water static pressure.

The PISO algorithm for the non-steady flow has fast calculating speed and relatively high overall efficiency, which has been used for pressure-velocity coupling calculating. The method of body force weight was adopted for the pressure interpolation calculation. The two-order discrete was used to discretization the momentum equation and kinetic energy equation of the flow, while the one-order discrete was used to discretization the flow dissipation rate equation. The under-relaxation factor of the PISO algorithm was very important for the calculating convergence, which has been adjusted according to the convergence residuals in the calculating process. In the iterative calculating process, the calculating convergence could be stabilized when the values of pressure, density, body force, momentum, turbulence kinetic energy, turbulence dissipation rate and turbulent viscosity were 0.6, 1, 1, 0.1, 0.8, 0.5 and 0.7.

4. Toilet Flushing Process Simulation

During the flushing, the water flowing out from the tank washes the inner wall surface of the toilet-basin through the circle arranged nozzles which at same time can spin up the water in the water package to promote the sewage discharging. The pressure of the flow directly links with the flow effective mechanical energy. The total pressure distribution of the flushing flow indicates the flow resistance at each sites of the toilet. If the local total pressure of some site varied by a big margin, the resistance of the flow could be estimated and the shape of this site would be adjust. The total pressure distributions of the flushing flow at the different time were shown as Fig.2.

According to the Fig.2, the water pressure at the bottom of water tank increased sharply at the time of 0.6s. This revealed that the kinetic energy of the flow couldn't increase immediately at the flushing initial stage. During the time of 1.4s to 2.5s, the total pressure of toilet-basin flow was increasing to about 200~400 Pascal, but this pressure was not high enough for washing the toilet-basin surface well. During the time of 2.5s to 3.5s, the dynamic pressure was big enough to push the pollutants out.

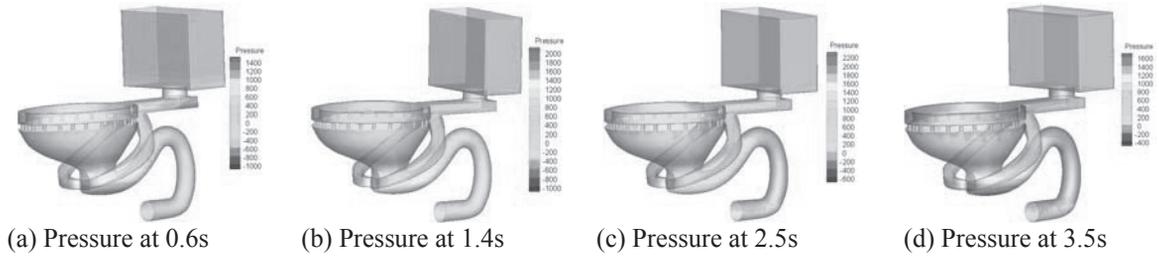


Fig. 2 Total pressure distributions of the flushing flow of the original toilet

According to the Fig.2, the water pressure at the bottom of water tank increased sharply at the time of 0.6s. This revealed that the kinetic energy of the flow couldn't increase immediately at the flushing initial stage. During the time of 1.4s to 2.5s, the total pressure of toilet-basin flow was increasing to about 200~400 Pascal, but this pressure was not high enough for washing the toilet-basin surface well. During the time of 2.5s to 3.5s, the dynamic pressure was big enough to push the pollutants out.

The big enough flow velocity at the toilet-basin surface was important for cleaning the surface. The distribution of the toilet-basin surface flow speed could display the effect of the surface being cleaned. The flushing flow speed at the toilet-basin surface point A was shown as Fig.3(b), which indicated that the big enough flow velocity greater than 1.5m/s sustained only for about one second, and this high speed flow duration was not long enough for cleaning the surface well.

The siphoning process at the siphon tube's top bent determined the capability of the muck been sucked thoroughly. The siphoning speed and its sustained time at the siphon tube's top bent point B were shown in Fig.3(c). This point's siphoning speed, which was big enough greater than 1.0m/s, appeared at the time from 3s to 4s and sustained only about 1s.

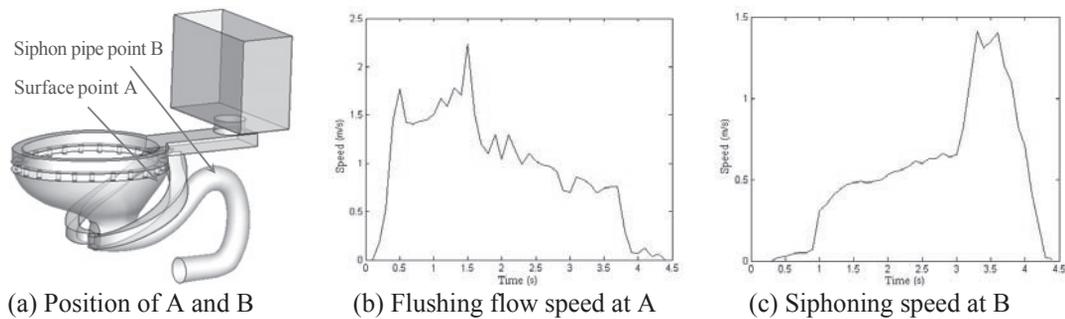


Fig. 3 Flushing flow speed and siphoning speed of the original toilet

The simulations for the original toilet revealed its performances were not satisfied design requires well, and its structure needed to be modified for improving its performances. .

5. Structure Adjust and its Performances

According the simulating results above, some sites' shape and structure of the toilet were adjusted like as the connection slope between sitting ring and the water tank pipe, the toilet-basin shape and the siphon tube bent figure etc. The simulations for the modified toilet were shown as Fig.4 and Fig.5.

The total pressure distribution of the modified model showed that the big enough speed flow duration had been lasted and the siphoning speed and its sustained time had been enhanced. That means that the simulation method is very efficiency and convenience for developing the high performance new-type toilet.

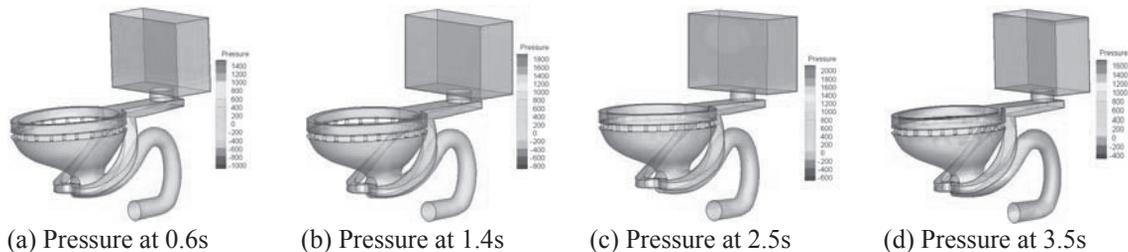


Fig. 4 Total pressure distributions of the flushing flow of the modified toilet

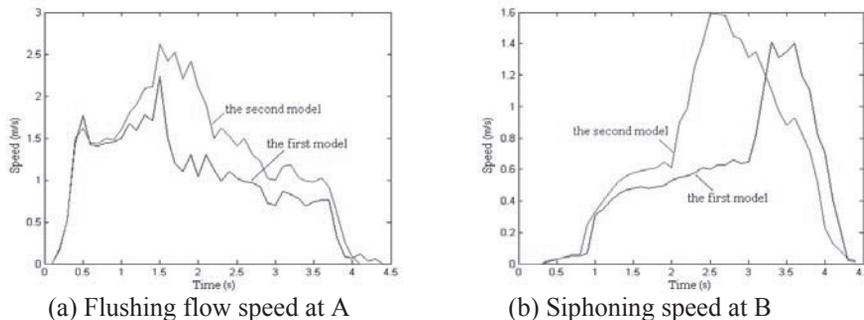


Fig. 5 Flushing flow speed and siphoning speed of the modified toilet

According to the simulation results above, some sites' shape and structure of the toilet were adjusted like as the connection slope between sitting ring and the water tank pipe, the toilet-basin shape and the siphon tube bent figure etc. The simulations for the modified toilet were shown as Fig.4 and Fig.5.

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6. Conclusion

The Realizable $k-\epsilon$ double equation model and VOF method for multiphase flow with free surface are suitable for simulating and analyzing the flushing flow of siphon toilet based on the digital wire frame technology. The performance of the toilet can be evaluated with the three-dimension flushing flow simulating method through the distribution of the two-phase flow field, the total flow pressure, the flow speed at the toilet-basin surface and the siphoning bent tube. Those have provided a high efficiency approach to develop new water-saving toilets.

Acknowledgement

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