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Performance Analysis and Improvement of Flat Torque Converters Using DOE Method

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Abstract

Automotive torque converters have recently been designed with an increasingly narrower profile for the purpose of achieving a smaller axial size and reducing weight. Design of experiment (DOE) and computational fluid dynamics (CFD) techniques are applied to improve the performance of a flat torque converter. Four torque converters with different flatness ratios (0.204, 0.186, 0.172, and 0.158) are designed and simulated first to investigate the effects of flatness ratio on their overall performance, including efficiency, torque ratio, and impeller torque factor. The simulation results show that the overall performance tends to deteriorate as the flatness ratio decreases. Then a parametric study covering six geometric parameters, namely, inlet and outlet angles of impeller, turbine, and stator is carried out. The results demonstrate that the inlet and outlet angles play an important role in determining the performance characteristics of a torque converter. Furthermore, the relative importance of the six design parameters is investigated using DOE method for each response (stall torque ratio and peak efficiency). The turbine outlet angle is found to exert the greatest influence on both responses. After DOE analysis, an optimized design for the flat torque converter geometry is obtained. Compared to the conventional product, the width of the optimized flat torque converter torus is reduced by about 20% while the values of stall torque ratio and peak efficiency are only decreased by 0.4% and 1.7%, respectively. The proposed new optimization strategy based on DOE method together with desirability function approach can be used for performance enhancement in the design process of flat torque converters.

Keywords: Torque converter, Flatness ratio, Computational fluid dynamics (CFD), Parametric study, Design of experiment (DOE)

1 Introduction

Torque converters are an important part of automatic transmissions in automobiles and other vehicles. It provides automatic torque amplification according to the different rotational speed between the input and output speeds without any active control, inherently suppressing engine torque fluctuations. Because it significantly affects the fuel economy, launch feeling and drivability, interests in the development of a high efficiency and performance have been increased recently.

In recent years, with the development of computer technology, computational fluid dynamics (CFD) has been widely used in hydraulic machine design and optimization. Zhao et al. [1] optimized a double-channel pump's impeller by combined using of CFD, multi-objective genetic algorithm (MOGA) and artificial neural networks (ANN). Li et al. [2] carried out an entropy production analysis to investigate the hump characteristics of a pump turbine based on CFD simulations. Shojaeefard et al. [3], Tan et al. [4] studied effects of some geometric parameters on fluid dynamic characteristics of a centrifugal pump by CFD. Many researchers have also studied the flows in torque converters by using CFD codes employing various methods [5, 6]. Since a number of variables are involved in the design of a torque converter, it is very difficult to achieve an optimal design. In order to improve the converter performance, it is required to obtain detailed understanding and relationship between the governing parameter and its effect on the performance, including efficiency, torque ratio and impeller torque factor. Kubo et al. [7] described the relationship between the design parameters used to define

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the geometry of an automotive torque converter and the resultant efficiency in relation to the internal flow characteristics. Shin et al. [8, 9] investigated the effect of reactor blade geometry with varying thickness ratios, scroll angles and slot angles on the performance of a torque converter. Song et al. [10] presented an integrated design process TDOS (Torque converter Design Optimization System) including torque converter geometry designer, 3D CFD analysis module, and design optimizer. The system was used to investigate the effect of design parameters on the performance.

Most passenger cars with small and medium size engines have adopted a front-wheel-drive layout in recent years. Torque converters accordingly have been designed with an increasingly narrower profile for the purpose of achieving a smaller axial size and reducing weight. A number of researchers have studied the flat torque converter employing both analytical and experimental methods. Ejiri et al. [11] manufactured and tested four torque converters with different flatness ratios. The experimental results show that the overall performance deteriorates when the flatness ratio is reduced to less than about 0.2. Kim et al. [12] investigated effects of the stator with two different shapes suitable for an axially squashed torus on hydraulic performance variation. Ochi et al. [13], Kietlinski et al. [14], and Usui et al. [15] developed new super-flat torque converters to provide free space for new equipments without much depreciation of efficiency. Abe et al. [16] employed newly developed stator blades to develop the fluid flow channels for a thin type torque converter with a flattening ratio of 50%, while maintaining torque converter performance. Yan et al. [17] proposed a flexible flat torque converter and estimated the influence of the flatness ratio on performance. Liu et al. [18] investigated the internal flow characteristics of the flat torque converter based on elliptical design path. However, there are no reports regarding combination effect of the blade geometry including inlet and outlet angles of impeller, turbine, and stator on the flat torque converter performance characteristics.

DOE method is widely used to find the importance level of the design parameters with respect to the optimization target and obtain the best combination of design variables. Park et al. [19] studied a methane-fueled gas engine generator with addition of hydrogen using DOE method. Hatami et al. [20] applied central composite design based on DOE to obtain an optimal design of the vane geometry for a variable geometry turbine. Taghavifar et al. [21] applied DOE evaluation to introduce the optimum injection strategy-chamber geometry of diesel engine. However, there have been relatively few applications of DOE method to flat torque converters optimization.

In this paper, the main objective is to improve the overall performance of a flat torque converter by using DOE method and CFD calculations. Firstly, performance characteristics of four torque converters with different flatness ratios are investigated. Then, the sensitivity analysis is used to analyze the influence of inlet and outlet angles of impeller, turbine, and stator on the performance of a flat torque converter. Finally, the optimization analysis is performed by using DOE post-processing analysis together with desirability function approach.

2 Flat Torque Converter Design

2.1 Torus Design

The flat torque converter design started with the definition of the torus shape. A torque converter with 250 mm nominal diameter was chosen as the prototype model. Elliptical design method was used to redesign the mean streamline of the torque converter and flatness ratio was redefined as the rate of major axis and minor axis. The redefined flatness ratio is represented by the symbol e in this paper. Given the flow area in the circular path, in the proposed torque converter model, was assumed constant, the shell and the core shapes were also redesigned. The torus design result compared with prototype model torus is shown in Figure 1.

As shown in Figure 1, the redesigned torus shows good agreement with the prototype model torus so that it could be used to design flat torque converters. Four torque converters with different flatness ratios were designed and referred to here as type 1 to type 4, in decreasing order of flatness ratio, as shown in Table 1.

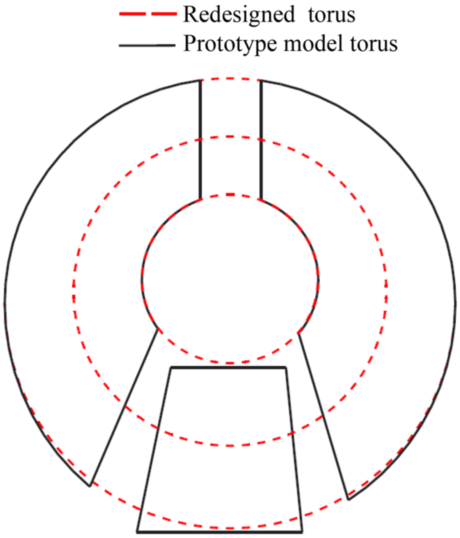

Figure 1 Comparison of redesigned torus with prototype model torus

Table 1 Parameters of torus with different flatness ratios

Parameters	Type 1	Type 2	Type 3	Type 4
Nominal diameter *D* (mm)	250	250	250	250
Width of torus *W* (mm)	51	46.40	42.95	39.53
Flatness ratio e_0	0.204	0.186	0.172	0.158
Redefined flatness ratio *e*	1.0	0.9	0.8	0.7

Figure 2 illustrates the approach to shorten the axial dimension of the fluid flow channel. The torus could be flattened without changing the inlet radius R_1, and outlet radius R_2 of each blade element. The design parameters were unchanged as much as possible except the flatness ratio and the stator axial length was proportional to the torque converter axial length. In this present paper, four types of torus with different flatness ratio are designed using the same method.

2.2 Blade Design

The impeller and turbine blades were designed to match the flat torus without changing in their inlet and outlet angles on the design path, a curve that bisects the flow passage cross-sectional area. The impeller had 31 blades and the turbine had 29 blades, which all had the thickness of 1.0 mm. The blades of four different stators all had the same distribution of thickness, it features relatively thick profile, which was better hydraulic performance than thin blades. They were also identical to each other inlet and outlet angle except for shapes. The inlet and outlet angles on the design path for the three elements are shown in Table 2.

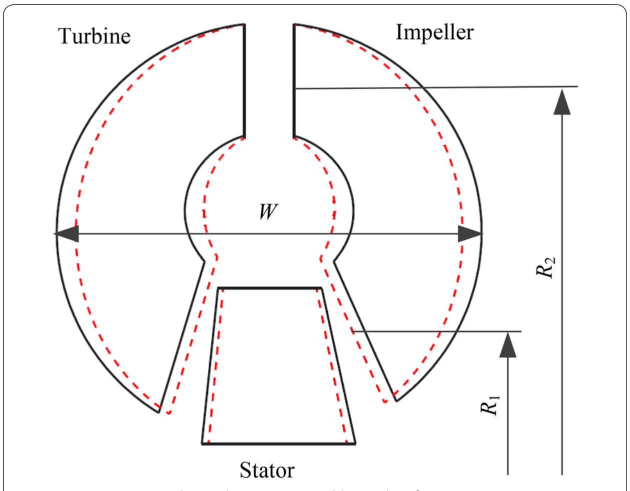

Figure 2 Approach to decrease axial length of torus

Table 2 Inlet and outlet angles of three elements

Parameters	Impeller	Turbine	Stator
Inlet angle β_1 (°)	131	34	97.5
Outlet angle β_2 (°)	50	144	21

3 Flat Torque Converter Design

3.1 Computational Method

To represent the complex geometry of a torque converter and generate the computational mesh in an appropriate way, ICEM and Pro/Engineer respectively, were used. The computational mesh is given in Figure 3 where one blade passage is shown for each element to illustrate the mesh distribution in the computational field when about 81,000 grid cells in total were used. The leakage between the elements and also between an element and the core flow were disregarded. A cyclic boundary condition was imposed on both peripheral boundaries outside a blade passage. A no-slip wall boundary condition was also imposed on all the walls bounding the domain, with a spin applied as necessary. The interfaces between elements have been handled by using the explicit multiple reference frame (MRF) method which allows the problem to be solved in a different rotating reference, instead of a transient moving mesh. The inherent advantage of the MRF approach was the ability to build the computational mesh of each of the rotating components independently. A second-order upwind differencing scheme was utilized and the standard *k*-*ε* model was also used for the turbulence. Steady state simulations were performed for a range of speed ratios from 0.0 to 0.9 while maintaining an impeller speed of 2000 r/min.

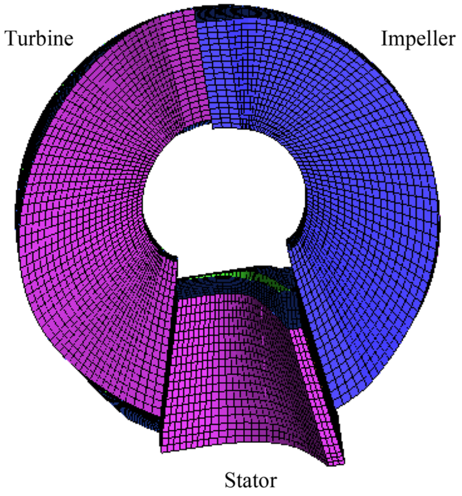

Figure 3 Computational mesh

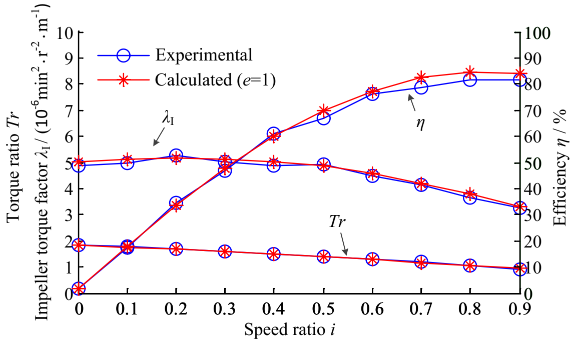

Figure 4 Overall performance of type 1 torque converter

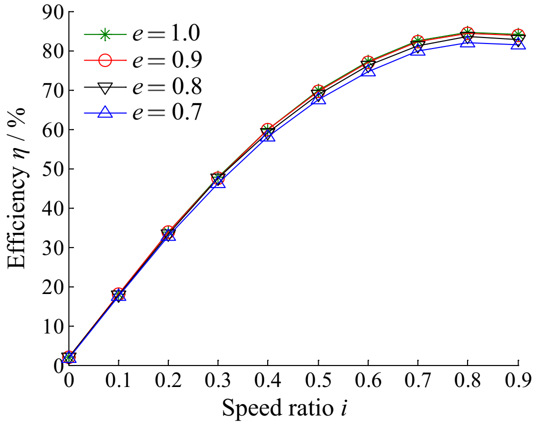

Figure 5 Efficiency of four different types

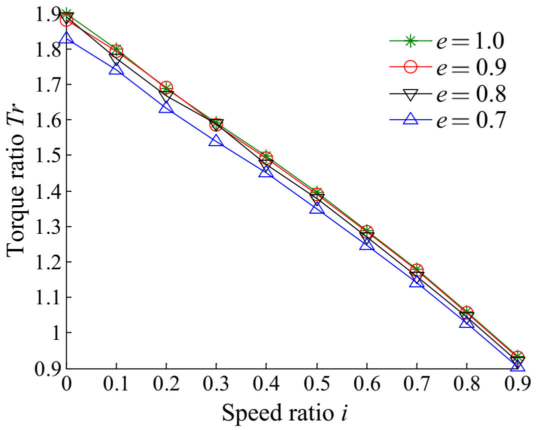

Figure 6 Torque ratio of four different types

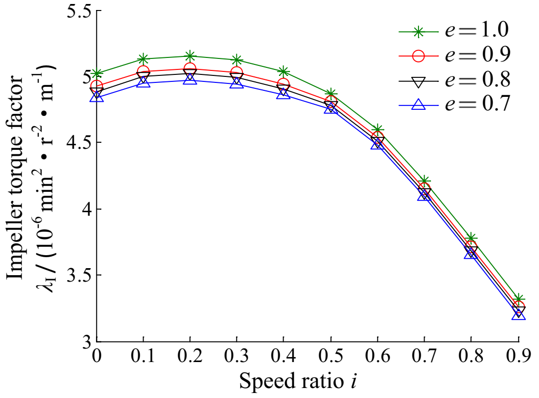

Figure 7 Impeller torque factor of four different types

3.2 Results and Discussion

Four torque converters with different flatness ratio were calculated using a CFD code in order to evaluate the change in their overall performance, including efficiency η, torque ratio Tr and impeller torque factor λ_{I}. The accuracy of the evaluation results was highly dependent on the accuracy of the CFD results. Therefore, it was important to obtain reliable CFD results. Figure 4 compares the measured and calculated overall performance for the type 1 torque converter. As indicated here, the tendencies of the experimental data correlated relatively well with the calculated results, confirming that the computational method is valid in general.

Figure 5 shows the overall efficiencies calculated for all four types of torque converters. As the flatness ratio e decreases, the overall efficiency decreases, which is quite remarkable at high speed ratio. The main cause of this decline in overall efficiency was attributed to a greater loss within the fluid flow channels due to flattening. Figure 6 describes the torque ratio Tr versus the speed ratio i with four types of torque converters. It is of note that the type 2 ($e = 0.9$) has nearly the same values with the reference type ($e = 1.0$), and the other types show the lower torque ratio throughout the whole range of speed ratios. Figure 7 illustrates the impeller torque factor comparison among the four types. Among the four types, the type 4 ($e = 0.7$) shows the lowest value of impeller torque factor λ_{I}. When the flatness ratio e decreases, the magnitude of the impeller torque factor λ_{I} tends to decrease especially at low speed ratio. Based on the results in Figures 5, 6, 7, it is concluded that the overall performance tends to deteriorate as the flatness ratio e decreases.

4 Optimal Design of a Flat Torque Converter

The trend in future automatic-transmission designs is to achieve comparable performance to traditional designs but with reduced mass and in less space. The challenge in torque converter design is to develop a reduced-width torus without sacrificing performance. In this paper, CFD is used to analyze numerous iterations of torque converters to optimize the torus for the allowed space. The type 4 torque converter with flatness ratio 0.158 ($e = 0.7$) was chosen as the study object.

4.1 Sensitivity Analysis of Inlet and Outlet Angles

Since the blade transmits all of the torque of a torque converter, its design is of utmost importance. In fact, each of the blades would receive working fluid without shock, deflect the flow smoothly throughout the length of blade passage, and discharge the fluid at the optimum angle at all conditions of speed ratio and torque distribution. Unfortunately, it is very difficult to meet optimal requirements. In the present study, a sensitivity analysis was used to investigate the effect of the blade geometric parameters on the torque converter performance characteristics. The main parameters investigated in this paper were inlet and outlet angles of the impeller, turbine, and stator. To improve the design efficiency, a software was developed for generating the blades with various inlet and outlet angles [22]. The blades of type 1 torque converter with inlet and outlet angles shown in Table 2 were chosen as the reference blades in order to compare the performances of the others. Finally, blades of the impeller, turbine, and stator with various inlet and outlet angles (5°, 10°, or 15° below and above the reference value of the parameter) were generated.

Torque converters with different blades were calculated using the above-mentioned computational method in order to evaluate the effect of inlet and outlet angles on their overall performance, including peak efficiency η^* and stall torque ratio Tr_0. Figure 8 shows the sensitivity of impeller inlet and outlet angles on the performance characteristics of the converter. The impeller inlet angle β_{I1} ranges from 115° to 145° while the outlet angle β_{I2} ranges from 35° to 65°. In the range of β_{I1}, performance Tr_0 decreases with increase of angle, whereas η^* increases. Conversely, the increase of β_{I2} causes increase of Tr_0 and decrease of η^*. Figure 9 provides the sensitivity of turbine inlet and outlet angles on the performance characteristics of the converter. The turbine inlet angle β_{T1} ranges from 20° to 55° while the outlet angle β_{T2} ranges from 120° to 155°. It is of note that the torque converter with reference blades shows the highest value of Tr_0 among simulation cases with different β_{T1} and highest value of η^* among simulation cases with different β_{T2}. The simulation case with β_{T1} five degree lower than the reference blade shows drastically decreases in η^*. It is seen that Tr_0 decreases with increase of β_{T2}. Figure 10 illustrates the sensitivity of stator inlet and outlet angles on the performance characteristics of the converter. The stator inlet angle β_{S1} ranges from 80° to 115° while the outlet angle β_{S2} ranges from 5° to 40°. Similarly, the simulation case with reference blades shows the highest Tr_0 value among cases with different β_{S1}. Performance η^* increases first and then decreases with increase of β_{S1}. It is found that both performance Tr_0 and η^* decrease with increase of β_{S2}.

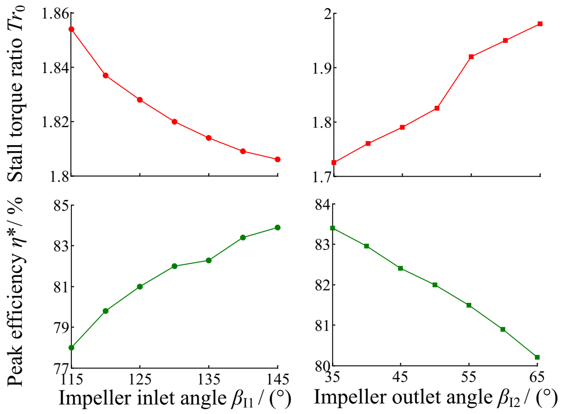

Figure 8 Impeller inlet and outlet angles sensitivity analysis

Based on the results in Figures 8, 9, 10, it is concluded that the inlet and outlet angles of the impeller, turbine and stator play an important role in determining the performance characteristics of a torque converter including stall torque ratio and peak efficiency. The sensitivity analysis provides useful information of the influence of design parameters individually on the flat torque converter, but not provides information on their combinations effect. Later, a DOE technique would be used to gauge the combination effect of these six dominant parameters.

4.2 DOE Method

Design of experiments (DOE) is a collection of mathematical and statistical techniques to reduce the number of experiments in order to find the effect of parameters affecting a response in a process, thereby aiming for a reduction in both costs and time [23–25]. It is also useful to obtain a great deal of information through an action to reduce the number of simulations. The aim is to select some points that the numerical simulations should be investigated and can be adopted for planning, conducting, analyzing, and interpreting controlled tests in order to evaluate the factors that control the value of a parameter or group of parameters. A DOE method sets out configurations (or arrangements) to be conducted using an appropriate orthogonal array; the terminology used in these arrays includes "factors"—an item that is to be varied during the simulations, "level"—the number of times a factor is to be varied during the simulations and "configuration number"—the number of simulations that are required to be run to complete the analysis [26]. For this paper six main geometrical parameters of a torque converter are selected as design variables (factors), which are the inlet and outlet angles mentioned above. For each design parameter, five different values (levels) were assigned. So 25 ($L_{25}[5^6]$) configurations with different combinations were generated for DOE. The original values of the six parameters are listed in Table 2 and the

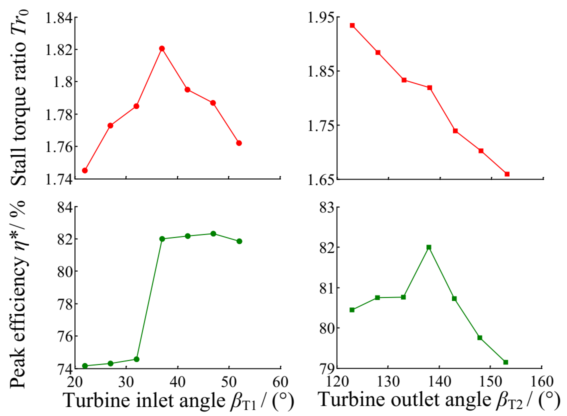

Figure 9 Turbine inlet and outlet angles sensitivity analysis

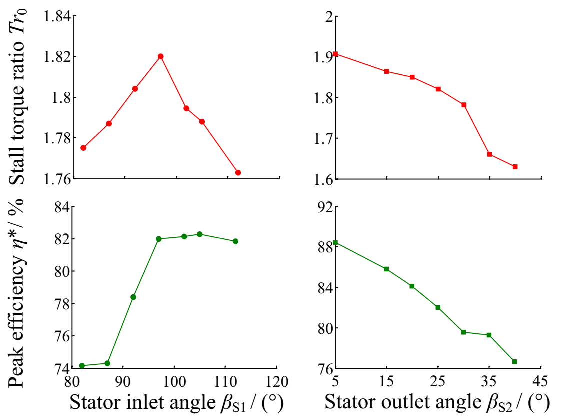

Figure 10 Stator inlet and outlet angles sensitivity analysis

step values were chosen to be 3° for each factor. The final configurations for DOE can be constructed as shown in Table 3.

4.3 Numerical Simulation

The 25 cases with different blade dimensions were simulated using the above-mentioned method. Stall torque ratio and peak efficiency were selected as the dynamic characteristic and economic characteristic, respectively, to evaluate the performance characteristics of the flat torque converter. The simulation results are also presented in Table 3. It can be seen that among the cases, numbers 14 and 19 have the two best results of stall torque ratio, and number 19 and 15 have the two best results of peak efficiency. It is clear that the maximum stall torque ratio and the maximum peak efficiency can not be obtained at the same time. So, an optimization study is needed to improve the overall performance of the flat torque converter.

4.4 DOE Post-processing and Optimization

The processing of the data obtained from DOE could be described as below. Firstly, the 25 cases were grouped by the levels of a factor. Taking factor turbine inlet angle β_{T1} as example, five groups could be obtained and each of them had the same value (as shown in Table 3). The average value of the stall torque ratio Tr_0 of each group could be calculated as follows:

$$K_1 = \frac{1.7996 + 1.8055 + 1.8359 + 1.8055 + 1.7852}{5} = 1.80634, \tag{1}$$

$$K_2 = \frac{1.7621 + 1.7961 + 1.8014 + 1.8147 + 1.8199}{5} = 1.79884, \tag{2}$$

$$K_3 = \frac{1.7699 + 1.7996 + 1.8269 + 1.8455 + 1.8347}{5} = 1.81532, \tag{3}$$

$$K_4 = \frac{1.7806 + 1.7982 + 1.7717 + 1.8426 + 1.8364}{5} = 1.8059, \tag{4}$$

$$K_5 = \frac{1.7998 + 1.7516 + 1.7817 + 1.7995 + 1.8106}{5} = 1.78864, \tag{5}$$

To be more clear, the influence levels K_1, K_2, K_3, K_4, and K_5 were the average stall torque ratio when turbine inlet angle β_{T1} equaled 28°, 31°, 34°, 37°, and 40°, respectively. Then, the peak efficiency could be processed by the same method. In addition, range R was defined as the difference between maximum and minimum values. Finally, the overall DOE analysis data was calculated and shown in Table 4.

The range R reflects the influence level of each geometrical parameter on the hydrodynamic characteristics of a torque converter. The contribution value C was defined as the percentage of the R value of a specific factor to the total R values of all the factors. A factor with larger R would have more influence on torque converter performance indicators, and was considered as an important factor during converter design. While factors with small range value R would be considered as less important factors during design procedure. It could be found in Table 4 that, parameters turbine outlet angle β_{T2} and stator outlet angle β_{S2} are the two most important factors. To be more precise, the descending sort of range R is $\beta_{\mathrm{T2}} > \beta_{\mathrm{S2}} > \beta_{\mathrm{T1}} > \beta_{\mathrm{S1}} > \beta_{\mathrm{I2}} > \beta_{\mathrm{I1}}$ for stall torque ratio, and $\beta_{\mathrm{T2}} > \beta_{\mathrm{S2}} > \beta_{\mathrm{T1}} > \beta_{\mathrm{I2}} > \beta_{\mathrm{I1}} > \beta_{\mathrm{S1}}$ for peak efficiency. Therefore, more focuses are needed on the

Table 3 Configurations and simulation results in DOE

Case number	Factors						Responses	
	Turbine inlet angle β_{T1} (°)	Turbine outlet angle β_{T2} (°)	Impeller inlet angle β_{I1} (°)	Impeller outlet angle β_{I2} (°)	Stator inlet angle β_{S1} (°)	Stator outlet angle β_{S2} (°)	Stall torque ratio Tr_0	Peak efficiency η^* (%)
1	28	138	125	44	91.5	15	1.7996	80.96
2	28	141	128	47	94.5	18	1.8055	81.65
3	28	144	131	50	97.5	21	1.8359	82.98
4	28	147	134	53	100.5	24	1.8055	81.23
5	28	150	137	56	103.5	27	1.7852	80.36
6	31	138	128	50	100.5	27	1.7621	78.34
7	31	141	131	53	103.5	15	1.7961	79.17
8	31	144	134	56	91.5	18	1.8014	80.29
9	31	147	137	44	94.5	21	1.8147	80.37
10	31	150	125	47	97.5	24	1.8199	80.11
11	34	138	131	56	94.5	24	1.7699	77.19
12	34	141	134	44	97.5	27	1.7996	79.82
13	34	144	137	47	100.5	15	1.8269	82.36
14	34	147	125	50	103.5	18	1.8455	82.76
15	34	150	128	53	91.5	21	1.8347	83.21
16	37	138	134	47	103.5	21	1.7806	79.24
17	37	141	137	50	91.5	24	1.7982	81.25
18	37	144	125	53	94.5	27	1.7717	79.53
19	37	147	128	56	97.5	15	1.8426	83.24
20	37	150	131	44	100.5	18	1.8364	81.71
21	40	138	137	53	97.5	18	1.7998	80.21
22	40	141	125	56	100.5	21	1.7516	77.59
23	40	144	128	44	103.5	24	1.7817	79.24
24	40	147	131	47	91.5	27	1.7995	78.47
25	40	150	134	50	94.5	15	1.8106	81.56

Table 4 Overall DOE analysis data

Indicator	Influence level	Turbine inlet angle β_{T1}	Turbine outlet angle β_{T2}	Impeller inlet angle β_{I1}	Impeller outlet angle β_{I2}	Stator inlet angle β_{S1}	Stator outlet angle β_{S2}
Stall torque ratio Tr_0	K_1	1.80634	1.78240	1.79766	1.80640	1.80668	1.81516
	K_2	1.79884	1.79020	1.80532	1.80648	1.79448	1.81772
	K_3	1.81532	1.80352	1.80756	1.81046	1.81956	1.80350
	K_4	1.80590	1.82156	1.79954	1.80156	1.79650	1.79504
	K_5	1.78864	1.81736	1.80496	1.79014	1.79782	1.78362
	R	0.02668	0.03916	0.00990	0.02032	0.02508	0.03410
	C	17%	25%	7%	13%	16%	22%
Peak efficiency η^* (%)	K_1	81.436	79.188	80.190	80.420	80.836	81.458
	K_2	79.656	79.896	81.136	80.366	80.060	81.324
	K_3	81.068	80.880	79.904	81.378	81.272	80.678
	K_4	80.994	81.214	80.028	80.670	80.246	79.804
	K_5	79.014	81.390	80.910	79.734	80.154	79.304
	R	2.022	2.202	1.232	1.644	1.212	2.154
	C	19%	21%	12%	16%	12%	20%

optimization of turbine outlet angle and stator outlet angle in the design phase, in order to achieve better performance of the flat torque converter. It should be noted that the results may have some difference with the conclusions studied before. This is possible caused by the level selection of design parameters. In the present study, the desirability function was used to carry out the optimization [27]. The optimization results depend on the response weights of stall torque ratio and peak efficiency. In this study, optimization analysis was performed provided that the stall torque ratio and peak efficiency had the same response weight. The results show that case 19, that is, 37° for β_{T1}, 147° for β_{T2}, 128° for β_{I1}, 56° for β_{I2}, 97.5° for β_{S1}, and 15° for β_{S2}, have the best overall performance of the flat torque converter. Compared to the conventional product ($e = 1.0$), the flat torque converter with flatness ratio 0.158 ($e = 0.7$) is developed that reduce the width of the torus by about 20%. The axial length of the optimal flat torque converter and its weight have been substantially reduced while the values of stall torque ratio and peak efficiency are only decreased by 0.4% and 1.7%, respectively.

5 Conclusions

1. DOE method based on CFD technique is applied to obtain an optimized design of a flat torque converter geometry. To this end, 25 cases with different inlet and outlet angles of impeller, turbine, and stator are designed, constructed and simulated. The main advantage of DOE is its ability to consider the combination effect of design parameters on performance, as it is not limited to traditional one-factor-at-a-time approach.
2. The analysis of the DOE array identified the dominant geometrical influences on the performance of the flat torque converter. In general, the turbine outlet angle and stator outlet angle are the two strongest influences on the converter performance characteristics, including stall torque ratio and peak efficiency.
3. Based on the calculation results in DOE, desirability function approach is employed to optimize the flat torque converter geometry. It should be noted that the maximum values of stall torque ratio and peak efficiency can not be obtained at the same time. Finally, the best design configuration is achieved at case 19, that is, 37° for turbine inlet angle, 147° for turbine outlet angle, 128° for impeller inlet angle, 56° for impeller outlet angle, 97.5° for stator inlet angle, and 15° for stator outlet angle. The optimization method first used in performance improvement of flat torque converters can provide fundamental guidelines for designers.

Authors' Contributions

G-QW and JC were in charge of the whole trial; JC wrote the manuscript; JC and W-JZ assisted with sampling and laboratory analyses. All authors read and approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests.

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