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Numerical Study of Performance of a Torque Converter Employing a Power-Law Fluid

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Abstract

Torque converter (TC) is a totally enclosed hydrodynamic turbomachine, used most often in automobiles for the smooth transmission of power and speed change from the engine to the transmission, and torque magnification. A typical TC has 3 major components: a pump that is attached directly to the TC cover and connected to the engine shaft, a turbine connected to the transmission shaft, and a stator connected to the transmission housing via a one-way clutch and providing guidance for the fluid flow. In this work, performance of a TC employing a power-law fluid is investigated numerically, using a commercial Computational Fluid Dynamics (CFD) software package. The standard k-epsilon turbulence model is used. A power-law fluid whose zero-shear properties correspond to an industrial oil is used for the working fluid. It is found that as the power-law index increases so that the fluid behaviour varies from being shear-thinning through Newtonian to shear-thickening, both efficiency and torque ratio decrease slightly. Also, the change is more pronounced at lower speed ratio.

Introduction

The main focus of this study is to present the effects of the power-law index on the performance of a torque converter employing a power-law fluid. This will help us to develop a more efficient torque converter, which will result in vehicles with better fuel economy. Fuel economy is important; both because the world's natural resources are limited and because environmental pollution has already reached unacceptable level. As billions of torque converters are used every day all over the world, the slightest improvement in efficiency will result in a significant contribution. This will be an enhancement of the fuel economy, and will enable to decrease operating cost and pollution.

A torque converter is a complex hydrodynamic turbo-machine; see figure 1 [9]. The closed-loop multi-component structure makes it complex. A typical torque converter has three major components (1) a pump, which is attached directly to the cover of the torque converter and connected to the engine shaft; (2) a turbine, which sits freely inside the casing and provides power to the transmission shaft; (3) a stator, which is attached to the transmission housing through a one-way clutch. The stator is placed in between the turbine exit and the inlet of the pump. The function of the stator ideally is to redirect the fluid to obtain a zero flow incidence into the pump at a certain designed speed ratio (turbine-speed/pump-speed). It also acts as a torque reactor at a low speed ratio, providing the torque amplification, thus differentiating the torque converter from the conventional fluid coupling. Different structural arrangements can cause variations to the fluid flow inside the torque converter. The structural arrangements could be on the basis of the blade numbers, blade angles, tip-bending, and size of the components of the torque converter, or other factors. The long narrow passages with curve and varying cross-sectional shapes cause the fluid flow to be very complex in this turbo-machine. This complex three-dimensional fluid flow is dominated by rotational speed, secondary flows, viscous effects and separation. The fluid flow is also dependent on the performance parameters, such as speed ratio, torque ratio (turbine-torque/pump-torque), capacity factor, and K factor. In order to obtain a more efficient torque converter, a detailed understanding of the fluid flow is essential.

Fujitani et. al. [6] computed the flow inside a torque converter with an assumption of inlet boundary condition for each element (pump, turbine and stator) being the same to the outlet boundary condition of the upstream-side element. Abe et al [1] obtained a very strong three-dimensional and secondary flow by computing the internal flow field of a torque converter using a steady interaction technique and a third-order upwind scheme. Schulz, Greim and Volgmann [11] utilised a numerical method for the three-dimensional fluid flow-field in a torque converter, using steady or unsteady incompressible viscous flow to calculate the flow field. By and Kunz [2] computed the flow field in the pump of a torque converter using a modified Navier-Stokes code. They concluded that the inlet velocity profile strongly affects the total pressure loss and that the nature of the secondary flow field strongly depends on the pump rotation. Marathe et al [10] utilized a two-dimensional, steady, incompressible Navier-Stokes code to get the mid-span flow field of the stator. For the designed condition, the calculated mid-span flow was accurate, but the off-design condition was not so.

Tsujita and Mizuki [14] experimented with a three-dimensional, incompressible, turbulent flow in the pump of an automotive torque converter. They tried at three different speed ratios (0.02, 0.4 and 0.8), while keeping the same inlet boundary condition. A k-ε model was used for turbulence. The computed result was satisfactory compared to the experimental data. In keeping with the growing use of CFD software, Cigarini and Jonnavihula [3] simulated a three-dimensional fluid flow for an automotive torque converter using the STAR-CD package. They applied the steady interaction technique implemented in that fluid dynamic program. The computed performance characteristics agreed well with the experimental ones. In order to improve the torque converters efficiency, Ejiri and Kubo [4, 5] also carried out a viscous calculation using STAR-CD, and modified the torque converter. The computational result was reasonably close to the actual flow pattern. Continuing with their research, they also concluded that for the maximum overall torque converter efficiency, there is an optimum value for a turbine angle and the contraction ratio of the pump passage.

Yang et al [15] carried out a computational flow analysis on a torque converter. They compared it with an experimental data and found their analysis to be satisfactory. In their paper they described the mixing-plane. The increasing pressure for pollution control and constant demand for higher fuel economic vehicle has lead Shin, Chang and Athavale [12] to investigate the flow field in an automotive torque converter. In 1999 they performed a numerical analysis to achieve a detailed incompressible, three dimensional, turbulent flow field within the pump of an automotive torque converter. They have used a modified Navier-Stokes flow code for the computation of the torque converter flow along with mixing plane and a k-ε turbulence model. Their numerical analysis showed remarkable similarity with experimental performance data in terms of torque ratio, efficiency and input capacity factor. Experimental data have also been presented in references [7-10,12].

On the other hand, the working fluid in torque converters can deviate significantly from being Newtonian; but the non-Newtonian effects on their performance don't seem to have been considered. Thus in this work, performance of a torque converter is investigated when the working fluid is non-Newtonian of power-law type. Specifically, effects of the power-law index are considered.

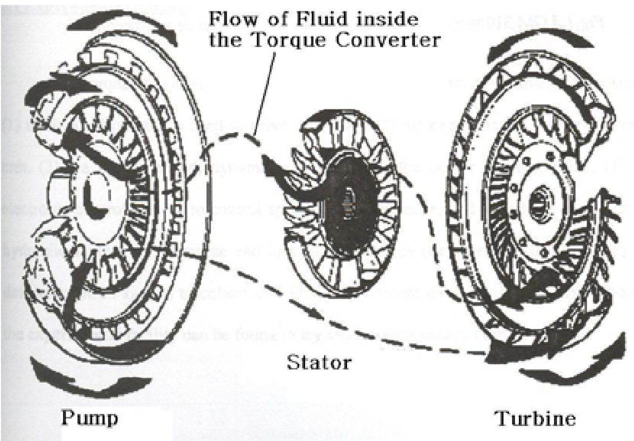

Figure 1. Torque converter fluid flow path [9].

Problem Description and Computational Method

Computation is conducted on a torque converter of about 230-mm of outer diameter. More specific dimensions are shown in the figure 2. The specifications for the torque converter's three elements are listed in table 1. The number of blades used in this torque converters' pump, turbine and stator are 29, 31 and 16 respectively. The gap between the pump and the turbine is 3 mm at both shell side and core side. In between turbine and stator, the gap is minimum 5 mm at the core side, and maximum 17 mm at the shell side. For stator and pump it is 5 mm at core side and 17.3 mm at shell side. Shell and core surface and the wall of the blade were given no slip wall boundary condition. In the gaps, mixing planes were modelled for data transfer across them. The blades of pump and turbine are of uniform thickness and made out of metal sheet. As the stator has considerable variable thickness, slope and bend, it is made of casting. One of each component was included in the simulation for better understanding of the fluid flow.

Detailed Computational Model

The complex three dimensional fluid flow was solved using the CFD package CFD-ACE of the ESI Group. The goal of this study is to provide a better understanding of three-dimensional fluid flow inside the stator (and other components) and hence improve performance of the torque converter. In this work the standard k-ε turbulence model is used. For differencing scheme, upwind method is used for all parameters. Figure 3 shows the three-dimensional model of the stator. The other elements of the torque converter (pump and turbine) were also modelled in similar fashion.

All the three components (pump, turbine and stator) were each given the same grid structure of 38 × 21 × 22 grid points, with 38 points in the streamwise (inlet to exit) direction, 21 in pitchwise (suction to pressure) and 22 in the spanwise (shell to core) direction. Simulation was carried out for 1000, 2000 and 2350 rpm of pump impeller speed with speed ratio (turbine-speed/pump-speed) in the range of 0.1 – 0.8 for each of them. A convergence criterion of reduction of relative residuals by 3 to 4 orders of magnitude is used throughout.

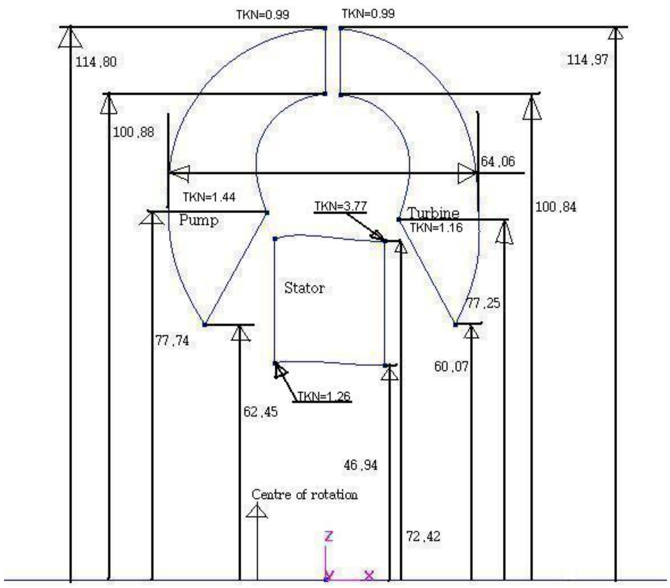

Figure 2. Dimensions (in millimeters) of the torque converter used in this work (TKN=Thickness of the blade).

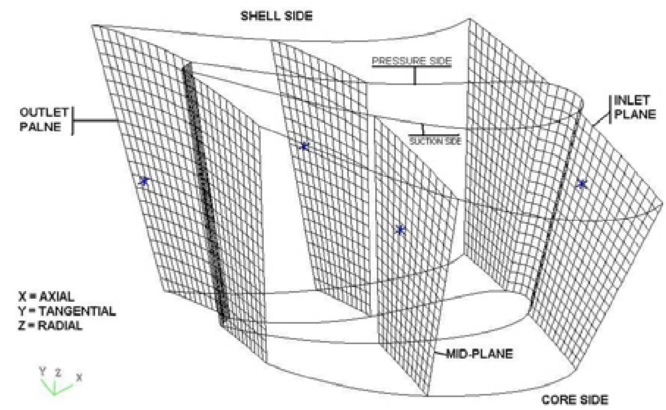

Figure 3. Inlet, Mid-chord and Exit plane of a stator.

Validation

Comparison is made between simulation results of this work and those of Shin et al [12]. Specifications for both torque converters (used in this work and in Shin et al's work) are shown in tables 1 and 2.

Comparison results are shown in figures 4 and 5. The difference is very small. Because Shin et al's work was shown to agree well with measurement data [12], confidence can thus also be accorded to this work's results.

Element	Inlet Angle – Degree	Exit Angle – Degree	Number of Blades
Pump	-16.3	– 4.75	29
Turbine	33.0	– 66.75	31
Stator	16.6	65.65	16

Table 1. Specifications of the torque-converter elements simulated in this work.

Element	Inlet Angle – Degree	Exit Angle – Degree	Number of Blades
Pump	-16.5	– 6.0	29
Turbine	49.5	– 57.5	31
Stator	16.5	72.0	16

Table 2. Specifications of the torque-converter elements used in Shin, Chang and Mahesh's SAE paper [12].

Results and Discussion

Simulation was performed at speed ratio of 0.2 for power-law index n in the range of 0.5 – 1.5. At the higher speed ratio 0.4 – 0.8 simulation was performed only with n = 0.5 – 0.9; difficulty with convergence was encountered at higher n values.

According to the figures 6 and 7, almost all results at different speed ratio (S.R.) show similar patterns of change, except for S.R. 0.6. This requires further investigation. It is evident that torque ratio (turbine-torque/pump-torque), as well as efficiency, decrease as the fluid property varies from being shear-thinning (n < 1) to Newtonian (n = 1); or, alternatively, torque converter's performance is enhanced with shear-thinning fluids.

On the other hand, with speed ratio 0.2, the shear-thinning fluid seemed to lose very little of its torque ratio and efficiency, as it approached being a Newtonian fluid. However, efficiency and torque ratio dropped substantially as the fluid becomes shear-thickening (n > 1). As power-law index increases further and the shear-thickening property becomes stronger, both torque ratio and efficiency decrease significantly further, before rising quickly as n approaches 1.5. A previous study [13] using Newtonian fluids showed that for 1000 rpm pump speed and 0.2 speed ratio, a torque ratio of 1.52 and efficiency of about 30% were obtained. In this work, at the same pump speed (1000 rpm) and speed ratio (0.2), a shear-thickening fluid with n = 1.5 results in torque ratio of 1.60 and efficiency 32.1%, a significant performance enhancement. Evidently, a lubricant whose viscosity increases quickly with higher shear (corresponding to n larger than about 1.4) alters strongly the flow field and the distribution of viscous forces, such that a reverse in the decreasing trend of torque ratio (and efficiency) occurs. To see how this happens requires detailed analysis of a complex flow; and this is a subject of further investigation.

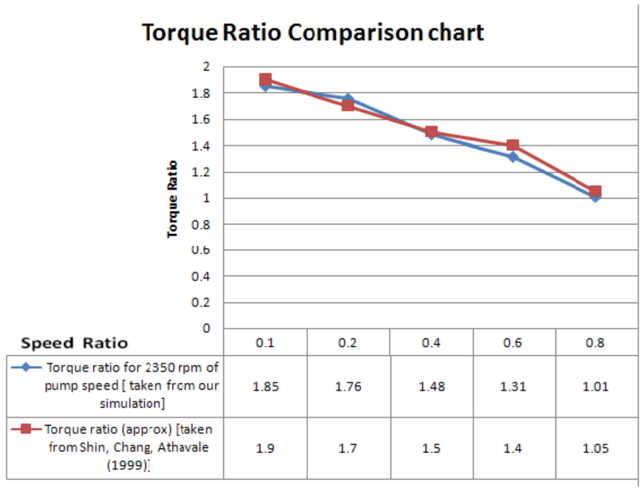

Figure 4. Comparison of torque ratio between this work and Shin et al's.

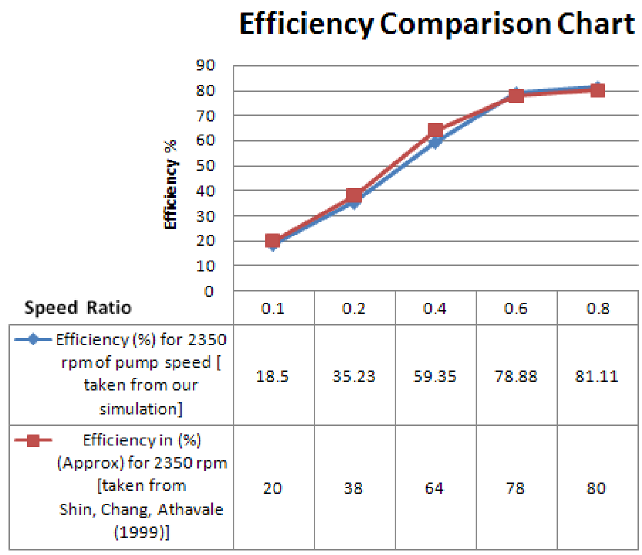

Figure 5. Comparison of efficiency between this work and Shin et al's.

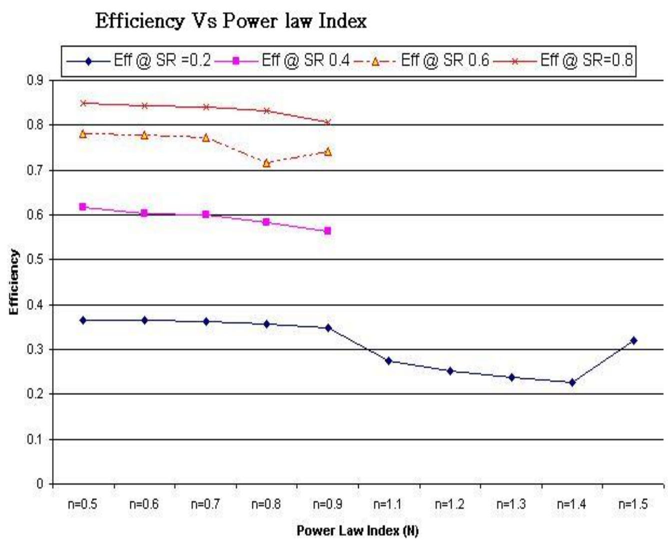

Figure 6. Torque-converter's efficiency vs. power-law index at different speed ratio.

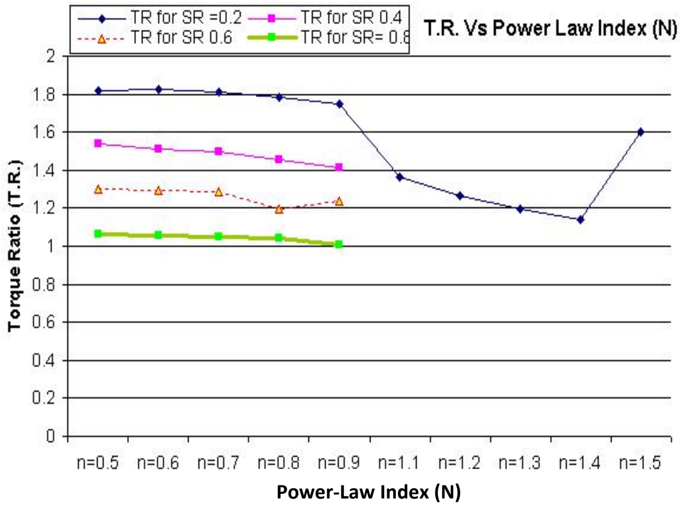

Figure 7. Torque-converter's torque ratio vs. power-law index at different speed ratio.

Conclusion

There was no sign of circulatory flows observed in the stator. There was no trace of flow separation observed in the stator. This research shows that the use of power-law fluids in a torque converter affects significantly the torque ratio (and efficiency). Torque-converter performance is enhanced using shear-thinning fluids; and as the power-law index n increases, both torque ratio and efficiency decrease. However, for the speed ratio of 0.2 when data are available, these decreasing trends revert to increasing with n when n is larger than about 1.4.

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