STEADY-STATE STRESS ANALYSIS IN A SUPERCRITICAL CO_2 RADIAL-INFLOW IMPELLER USING FLUID SOLID INTERACTION

by

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According to the geometry and the state parameters, a single channel model of a supercritical CO_2 radial-inflow turbine is established. The finite volume method, the finite element method, and the shear stress transport turbulence model are used for solid-fluid interaction. In 3-D finite element analysis, the results of flow analysis and thermal analysis are adopted to obtain the stress distribution of the impeller in working condition. The results show that the maximum equivalent stress of the impeller is 550 MPa, which is located at the blade root of trailing edge and lower than the yield limit. Meanwhile, the centrifugal load increases the stress level on the inside back end surface and the surface of the blade root of the trailing edge and increases the stress level in the downstream position of the impeller. The thermal load increases the stress level on the outside edge of the blade-end surface and the surface near the blade root of the blade root of the trailing edge and increases the stress level on the outside edge of the black-end surface and the surface near the blade root of the blade root of the trailing edge and increases the stress level on the outside edge of the black-end surface and the surface near the blade root of the leading edge.

Key words: *supercritical CO*₂, *radial-inflow turbine*, *solid-fluid interaction, stress distribution*

Introduction

Due to the relatively appropriate critical temperature and pressure (304.128 K, 7.38 MPa), the high density, the excellent flow characteristics and the security to apply to industrial production, supercritical CO_2 (SCO₂) is selected as one of the most promising fluid in energy conversion and transmission as well as in a power cycle [1, 2].

As a kind of prime rotating machine, a radial-inflow turbine can do work by converting the energy of the working fluid flowing along the radial channel into rotational kinetic energy. Because of the small flow rate, simple and reliable structure, easy fabrication, and 15% -50% higher internal efficiency than that of axial flow under low power [3], radial-inflow turbines are widely used in small energy conversion, such as engines of ships or vehicles, industrial-auxiliary steam turbines, *etc*.

Combining the advantages aforementioned, the SCO_2 radial-inflow turbine has a promising prospect in engineering application. However, in the working process of the turbine, the impeller bears the huge centrifugal load caused by the high speed and the pressure and thermal stress caused by the flow and heat transfer of the working fluid. Therefore, in order to

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ensure the safety and reliability of the key component, stress analysis in the impeller is necessary [4].

In recent years, scholars both home and abroad have taken extensive research work on strength analysis in radial-flow impellers, and finite element analysis (FEA) is often used as the mainstream of strength analysis in radial-flow impellers. Ramamuri and Balasubraminian [5] employed triangular plate element to calculate steady-state stresses of centrifugal fan impellers and checked the results using a strain gauge technique. Hamed *et al.* [6] studied the stresses of a radial-inflow turbine rotor associated with different cooling patterns by FEA and compared the projected blade life for the different cooling arrangements, taking centrifugal, thermal and aerodynamic load into consideration. Li [4] established the numerical computation model of the periodic cyclic symmetric impeller for a realistic radical-inflow turbine based on the strength and vibration FEA theory, and obtained the deformation, stress, natural frequency and vibration shape of the impeller under working condition. Zheng and Ding [7] used conjugate heat transfer analysis to obtain the temperature and surface pressure of the impeller and the results are adopted as boundary conditions for 3-D FEA to obtain the stress distribution of the axial-centrifugal combined compressor impeller. The effects of each load are compared.

Based on current researches, this paper uses a one-way fluid structure interaction to obtain the body temperature field and coupling surface pressure field of the single channel impeller, then the results are set as boundary conditions for 3-D structure FEA to obtain the stress distribution of the SCO_2 turbine impeller under working condition.

Methodology

The research object

This paper uses the impeller shown in fig. 1 as the research object, and the main geometric parameters is shown in tab. 1, where D_1 is the diameter of the impeller, l_1 , – the inlet height of blades, D_2 – the outlet outside diameter, D'_2 – the outlet inside diameter, β_1 – the inlet blade angle, β_1 – the outlet blade angle, and Z – the number of blade.

The alloy steel 2Cr12NiMoWV is selected as the impeller material, and the parameters are shown in tab. 2.

One-way fluid solid interaction

One-way fluid solid interaction refers to the unidirectional data transfer at the coupling interface. Generally, the results of fluid analysis are transmitted to the solid structure anal-



Figure 1. The radial-inflow impeller

Table 1. Geometry
of the radial-
inflow turbine

Parameter	Value			
D_1 [mm]	48			
<i>l</i> ₁ [mm]	1.87			
D_2 [mm]	29.50			
D'_2 [mm]	16.51			
β ₁ [°]	90			
β ₂ [°]	30.25			
Ζ	16			

ysis, while the results of solid structure analysis are not transmitted to the fluid analysis. It is commonly used in the case where the fluid analysis has a significant effect on the structural analysis, while the solid deformation is very small. This analysis method is just suitable for the stress analysis of the radial-inflow turbine impeller [8, 9].

In this paper, the effect of fluid on solid is considered. The fluid domain and the solid domain are coupled together in the CFD simulation, and the surface pressure load and the body temLin, Y., *et al.*: Steady-State Stress Analysis in a Supercritical CO₂ Radial-Inflow Impeller ... THERMAL SCIENCE: Year 2017, Vol. 21, Suppl. 1, pp. S251-S258

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Temperature [K]	293.15	373.15	473.15	573.15	673.15	773.15
Density [kgm ⁻³]	7840					
Young's modulus [GPa]	216	211	205	198	189	178
Shear modulus [GPa]	84.4	82.8	79.4	76.6	73.7	69.3
Poisson's ratio	0.279	0.273	0.291	0.293	0.319	0.275
Linear expansion coefficient [×10 ⁻⁶]	/	10.38	11.21	11.49	11.82	12.06
Specific heat capacity [Jkg ⁻¹ K ⁻¹]	530	/	585	627	663	721
Thermal conductivity [Wm ⁻¹ K ⁻¹]	24.3	27.7	28.1	29.1	29.1	29.7
Yield limit [MPa]	896	855	820	807	772	689

perature load on the impeller are calculated and set as the boundary conditions of 3-D structure FEA, so as to obtain the stress distribution of the impeller under the working condition.

The CFD simulation

The CFD simulation is conducted in the commercially available software ANSYS CFX. Considering the cyclical symmetry of the impeller model, the single channel model containing only two diffuser blades and an impeller blade is used to reduce the calculation time.

The calculation model is shown in fig. 2, where the blue part is the fluid domain, the red part is the solid domain, and the tetrahedron grid is adopted.

Here, the physical parameters of the working fluid SCO_2 are in accord with CO2RK in the database MA-TERIAL-redkw in ANSYS-CFX. The database is based on the Redlich Kwong equation, and provides a variety of amendments [11, 12].



Figure 2. The CFD calculation model (for color image see journal web site)

The inlet and outlet boundary conditions are given as follows: the total temperature and total pressure at the inlet of the diffuser is 617.36 K and 15 MPa, and the static pressure in the outlet of the impeller is 7.5 MPa. The global speed is 91500 rpm. The fluid-fluid interfaces between the impeller and the diffuser are coupled with the frozen rotor method, the fluid solid interfaces between the fluid domain and the solid domain are coupled by conservative heat flux, and the circumferential boundaries of the single channel model are coupled by rotational periodicity. The other fluid surfaces are set as adiabatic walls meeting the requirements of non-slip flow conditions, and the other solid surfaces are set as adiabatic walls.

In the solution of the fluid domain, the shear stress transport turbulence model is selected. The model is modeled by combining the k- ε turbulence model and the k- ω turbulence model with a weighted average way. The k- ω turbulence model is adopted at the wall surface, while the k- ε turbulence model is adopted in the area away from the wall. More accurate results are obtained in the flow with pressure gradient, and it has a wide range of applications in the solution of impeller internal flow [13, 14].

The 3-D structure FEA

The 3-D structural FEA is conducted in the commercially available software ANSYS Mechanical APDL. In the 3-D linear elasticity analysis with thermal load, the stress-strain relationship can be described [15]:

$$\varepsilon_x = \frac{1}{E} [\sigma_x - \mu(\sigma_y + \sigma_z)] + \alpha (T - T_0)$$
⁽¹⁾

$$\varepsilon_{y} = \frac{1}{E} [\sigma_{y} - \mu (\sigma_{x} + \sigma_{z})] + \alpha (T - T_{0})$$
⁽²⁾

$$\varepsilon_z = \frac{1}{E} [\sigma_z - \mu (\sigma_x + \sigma_y)] + \alpha (T - T_0)$$
(3)

where E is Youngs modulus of the material, μ – the Poissons ratio, α – the linear expansion coefficient, and T_0 – the referenced temperature.

The calculation model is shown in fig. 3. The boundary conditions are set:

- the axial constraint and the tangential constraint are set on the nodes of the front end (the outlet face of the working fluid), the tangential constraint is set on the nodes of the circumferential faces, the tangential constraint and axial coupling are set on the nodes of the back end, and the tangential constraint is set on the nodes of the inside surface, and
- the aerodynamic load is applied to the hub surface and the blade surface; the body temperature field and thermal load are applied to the impeller.



Figure 3. The FEA calculation model

Grid independence

In the process of CFD and FEA calculation, the different number of grids will affect the calculation results to a certain extent. In this paper, five different schemes for the number of grids are selected for the verification of grid independence of CFD and FEA calculation. The effect of the number of grids on the calculation results is checked by the change of the mass flow and the maximum equivalent stress (MES). The specific results are shown in tab. 3.

The numerical values of the flow rate and the MES of the sequence number 4 and 9 are basically stable. Considering the cost and precision of the calculation, the grid model with 428363 elements is selected for the fluid domain and the grid model with 271945 elements is selected for the solid domain.

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Results and analysis

Table 3. The verification of grid independence

Selection of monitored points

In order to compare the influence of each load on the stress distribution of the impeller, six nodes with high stress level are monitored, as shown in fig. 4, where the monitored point (MP) 1, 2, and 3 are located at the blade root, MP 4 is located at the outside edge of the back end, and MP 5, 6 are, respectively, located at the edge of the inside surface.

Tuble of The Vermeution of grid independence							
Sequence number	Number of elements (CFD)	Mass flow [kgs ⁻¹]	Relative error [%]				
1	142346	0.1656	/				
2	168325	0.1651	0.30				
3	256197	0.1644	0.42				
4	428363	0.1637	0.43				
5	527364	0.1636	0.06				
Sequence number	Number of elements (FEA)	MES [MPa]	Relative error [%]				
6	20810	472	/				
7	47954	431	8.69				
8	92130	447	3.71				
9	271945	550	23.0				
10	567636	544	1.09				

Results of CFD

The pressure and temperature distribution on the impeller surface and the

local magnification are shown in fig. 5. Figure 5(a) is the pressure contour. The distribution of isobars at the leading edge (LE) is very dense, where large pressure gradient exists and the global maximum pressure is about 12.89 MPa. Meanwhile, because the flow separation occurs when the SCO_2 from the outlet of the diffuser impact upon the LE of the impeller blade, the stagnation point emerges in the position of the pressure surface side near the LE, forming a low pressure area. The global pressure of the blade pressure surface is higher than the suction surface.

Figure 5(b) is the temperature contour, where the global temperature distribution is uniform and the maximum differ-

ence is only 34.52 K. The temperature of the blade is high, and the maximum temperature is located at the blade tip near the LE, reaching 576.01 K. The isotherms on the LE of the blade and the edge of the back end are closely distributed and the temperature gradient is large, which makes it easy to form large thermal stress. From the LE of the blade to the trailing edge (TE), the wall temperature decreases along the direction of the flow.

Results of FEA

In order to analyze the effects of centrifugal load, aerodynamic load and thermal load on the stress distribution of the impeller, each load is applied to the impeller for strength analysis separately and integrally in FEA.



Figure 4. Selection of MP



Figure 5. Pressure and temperature distribution (for color image see journal web site)

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Figure 6 is the contours of displacement vector under each load. Under the centrifugal load, the maximum displacement is located at the blade tip of the LE, reaching 0.00724 mm. Under the aerodynamic load, the maximum displacement is located at the suction surface with about 40% axial chord length, reaching 0.0119 mm. Under the thermal loading, the maximum displacement is located at the outside edge of the back-end surface, reaching 0.0899 mm. Under the total loads, the maximum displacement is also located at the outside edge of the back-end surface, with the value of 0.1 mm. The displacement under the thermal load is the highest and it is almost in accord with that under the total loads.

Figure 7 is the contours of Von-Mises stress under each load. The centrifugal load increases the stress level on the inside back end surface and the surface of the blade root, and MES is located at the blade root near LE on the suction surface, with the value of 197 MPa. The aerodynamic load causes significant stress concentration at the blade root of TE and increases the stress level in the downstream position of the impeller, and the MES is located at the blade root of TE, with the value of 466 MPa. The thermal load increases the stress level on the outside edge of the back end surface and the surface near the blade root of LE, but due to the small size and thermal inertia of the impeller, the global thermal stress level is low, and the MES is located at the outside edge of the back end surface, with the value of 62.5 MPa. The stress level

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is obviously highest under the total loads. Due to the stress concentration on the blade root of the TE, the MES reaches 550 MPa.

Conclusions

In this paper, the steady-state stress distribution of a SCO₂ radial-inflow turbine impeller is studied. The stress distribution of the impeller is obtained by applying the pressure field and body temperature calculated by CFD analysis. The CFD results are set as the boundary conditions of the 3-D structure FEA. Finally, the stress level of each load is analyzed at all MP. The main conclusions are as follows.

- Under the centrifugal, aerodynamic and thermal load, the maximum displacement reaches respectively 0.00724 mm, 0.0119 mm, and 0.0899 mm. Under the total loads, the maximum displacement reaches 0.1 mm. The displacement under the thermal load is obviously higher than that under other loads, and it is almost in accord with that under the total loads.
- The centrifugal load increases the stress level on the inside back end surface and the surface of the blade root. The aerodynamic load causes significant stress concentration at the blade root of TE and increases the stress level in the downstream position of the impeller. The

thermal load increases the stress level on the outside edge of the back-end surface and the surface near the blade root of the leading edge.

• The MES of the impeller is located at the blade root of TE with significant stress concentration, reaching 550 MPa. The stress of all MP is obviously lower than the yield limit, so the turbine impeller meets the strength requirement.

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Nomenclature

- *E* Youngs modulus, [GPa]
- T temperature, [K]

 T_0 –referenced temperature, [K]

 α –linear expansion coefficient, [–]

Greek symbols

 μ – Poisson's ratio, [–]

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