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SIMULATION FOR A NEW CASCADE OF HELIUM COMPRESSOR WITH ENHANCED PRESSURE RATIO

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ABSTRACT

The High Temperature Gas-cooled Reactor (HTGR) and external-combustion heat engine firing with non-traditional fuel bring Brayton-cycle helium turbine a very good prospect. If the helium compressor is designed according to conventional air-compressor rule, the compression ratio of single stage will be smaller and the number of stages will be excessive. These problems present a topic which must be solved in further development. Therefore a new velocity triangle of helium compressor is presented and analyzed. It can increase severalfold stage loading. The test data and experiences of air cascade are used to estimate the profile losses and stage efficiency of the new helium cascade. On the basis of validation for selected turbulence model and mesh division, fluid analysis software FLUENT6.3 is used to simulate the flow of new helium cascade. Simulation results show that, comparing with the conventional design, the new stage loading can be increased by 2 to 4 times when inlet Mach number is 0.466 to 0.7013. Therefore the stage number of helium compressor is reduced severalfold, while profile efficiency can reach 0.939 to 0.894; The air turning angle reaches 38.75° to 49.43°, while the outlet angle reaches 0.78° to -12.45°; There is basically no separating phenomenon in flow field. Because the experimental data are lacking to support the new cascade structural parameters and air cascade test is a kind of low-speed test, there is some deviation to estimate helium cascade performance at the higher Mach number by use of air cascade experiences. In this cascade simulation, traditional original profile thickness distribution (C-4 blade profile) is applied, therefore the optimizing for the profile thickness distribution and the shape of flow field are expected to be a greater potential for enhancing performance.

INTRODUCTION

At present, closed-cycle gas turbine is facing a good development opportunity[1-4], and it is mainly applied in two kinds of fuel and energy field: one is in high-temperature gas-cooled reactor (HTGR)[5-8]. The HTGR equipped with gas turbine has absolute advantage in efficiency and nuclear safety[9,10]; the other is in the heat engine with external-combustion system, and its applicable fuel is various, including coal, heavy oil, biological mass, metal, etc. The better working substance for the closed-cycle gas turbine is helium, whose inertia and neutron cross-section parameters make it applicable for the HTGR. High thermal conductivity and high constant-pressure specific heat of helium can make the size of heat exchanger reduce severalfold and make the flow area of compressor and turbine reduce sharply. The closed-cycle gas turbine studied currently almost takes helium as its working substance.

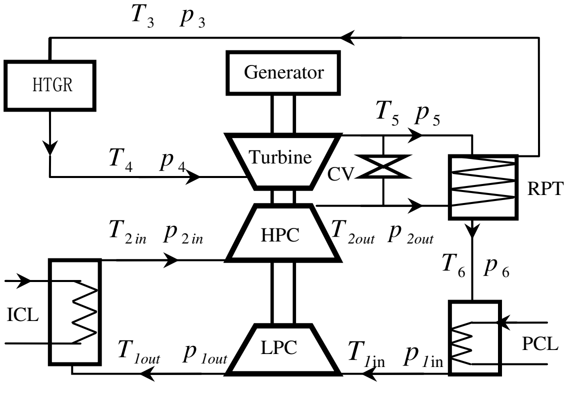


Figure 1 the HTGR helium turbine system

Figure 1 shows the HTGR helium turbine system. It is assumed that the low and high pressure compressors have the same pressure ratio and efficiency. The whole helium turbine system looks like a general complex cycle gas turbine power plant with reactor acting as combustion chamber. Here helium is the coolant of the reactor, the high temperature helium that comes from the reactor expands in the turbine to generate output power, the exhaust helium from turbine exchanges heat with the helium fluid from the outlet of the compressor. A precooler is placed in front of the low pressure compressor to reduce the inlet temperature, and an intercooler is placed between the compressors to lower the inlet helium temperature of high pressure compressor. The CV's (control valve) function is in case of electrical load rejection.

A 10MW high-temperature gas-cooled reactor (HTR-10) was constructed by the Institute of Nuclear and New Energy Technology (INET) at Tsinghua University of China. The helium turbine and generator system of 10MW high-temperature gas-cooled reactor (HTR-10GT) is the second phase for the HTR-10 project. It is to set up a direct helium cycle to replace the current steam cycle. In the closed Brayton cycle for the HTRs, the gas compressors, turbine and generator are all installed in the primary loop, whose shafts are supported by some kind of special designed bearings[11]. The helium turbine need be demonstrated which entails a helium test loop[12]. The turbine design must be demonstrated and most likely it will require fine-tuning on a test bench if the expected efficiency is to be reached. Besides, the first two wheels of the turbine will most likely need special material and their feasibility, from a technical point of view but also from an industrially economical viewpoint, will have to be demonstrated. The test will require some lifetime evaluation in view of the specific operating conditions.

The physical characteristics of helium and air are greatly different. For example, the acoustic speed of helium is three times as much as that of the air and the constant-pressure specific heat of helium is about five times than that of the air. Therefore the helium compressor and helium turbine are particular in aerodynamic performance. The test data and experiences of air gas turbine were accumulated in the past, so the mature design technologies applicable for air are normally applied to the current aerodynamic design of helium compressor, such as the air velocity triangle and the stage cascade.

Although the conventional method is easier to be grasped, some problems occur, such as excessive stage number. The reason is that the flow Mach number in conventional design is too small (only about 0.3) and so does the stage pressure ratio (for the same loading, when the stage pressure ratio of the air one is 1.2, the helium one is only 1.026). When designing the helium compressor with the same loading as the air-compressor, if eighteen stages are needed when the air pressure ratio is 20, ninety stages will be needed when the helium pressure ratio is 8.5 (At this point, the temperature ratio of the helium is the same as that of the air and the thermodynamic cycles is similar between them).

In the recent progress of study on HTR-10GT" project[13], the stage number of low-pressure and high-pressure helium compressor is eighteen totally, while the pressure ratio is only 2.5. The inlet temperature of closed-cycle turbine is 750℃. The turbine applies inter-cooling and regeneration technology (the best compression ratio of inter-cooling and regeneration cycle is lower than the one of simple cycle). With the heat source temperature of HTGR reaching up to 1000℃ and even higher, the cycle temperature ratio and pressure ratio need increasing higher, too. Such problem of excessive stage number will also occur in external-combustion Brayton-cycle helium turbine firing with non-conventional fuels.

According to what has been mentioned above, the problem of excessive stage number will exist if helium compressor is designed with the traditional air design rule. This problem will be more prominent along with the helium turbine applying and developing. In order to enhance the pressure ratio of helium compressor and reduce the stage number, a new cascade is conceptually introduced and the losses are estimated. The new cascade can prominently increase stage loading of helium compressor. The flow field of this new cascade is simulated by use of CFD software and the preliminary conclusions are presented.

NOMENCLATURE

C_p	specific heat
CFD	Computational Fluid Dynamics
ICL	Intercooler
PCL	Precooler
RPT	Recuperator
HPC	High-Pressure Compressor
LPC	Low-Pressure Compressor
CV	Control Valve
D	diffusion factor
$\overline{H}_{th}$	energy head coefficient=$\Delta W_u/U$
$K_{\Delta P\mathrm{s}}$	profile loss multiple
$K_{\Delta Wu}$	tangential velocity multiple
M	Mach number
P	total pressure
T	total temperature
U	tip speed
b	blade chord
c_p	pressure coefficient=$(P_1-p_l)/q_1$
i	incidence, $i=\beta_1-\beta_{1\kappa}$
p	static pressure
q	dynamic pressure
t	pitch
ΔP	total pressure loss
Φ	mass flow coefficient=C_z/U
α	angle of attack
β	airflow angle
$\beta_{1\kappa}$	blade inlet angle
$\beta_{2\kappa}$	blade outlet angle
δ	deviation, $\delta=\beta_2-\beta_{2\kappa}$
η_p	profile efficiency
η_s	isentropic efficiency

κ	specific heat ratio
π	stage pressure ratio
θ	airflow turning angle
ρ	degree of reaction
σ	solidity of blades=*b*/*t*

SUBSCRIPTS

l local condition
1 upstream of blade row
2 downstream of blade row

1. NEW VELOCITY TRIANGLE FOR HELIUM

For the new cascade design, it is necessary to change the traditional stage velocity triangle.

The typical velocity triangle of axial flow air-compressor is shown in Figure 2 and the stage parameters are illustrated in Table 1. The tip speed can only maintain the same as that of the air-compressor if this typical velocity triangle is adopted to design helium compressor. The tip speed is fixed at 300m/s, which is from the experience of the project of 10MW HTR-10GT and also reflects the level of the rotor structural strength of impeller. The airflow velocity is also the same as that of the air-compressor. The physical characteristics of helium (acoustic speed, constant-pressure specific heat, adiabatic exponent) is different from air, therefore the inlet Mach number of helium compressor is only about 0.3 (an example for 0.267 in Table 1) and the stage pressure rise is just about 12% of the air. The stage pressure ratio is very small.

Figure 3 is the new velocity triangle, it can prominently increase stage loading (Euler work $h = U \times \Delta Cu$) of helium compressor. This velocity triangle can be earlier found in reference [14]. The flow velocity can be increased severalfold up to middle subsonic by use of the characteristic of high acoustic speed of helium. As a result, the tangential velocity ΔCu can be increased severalfold and then the Euler work is also increased severalfold with the same tip speed. Comparing with the air typical velocity triangle, the airflow turning angle of this new velocity triangle is obviously increased and outlet angle tends to axial direction or even over to negative direction. The airflow turning angle of this new velocity triangle is large, it looks like, according to conventional experiences, that it is difficult to bear the diffusion load. However, from another point of view, the diffusion factor calculated by traditional method is not large. Therefore it is possible to realize this new velocity triangle.

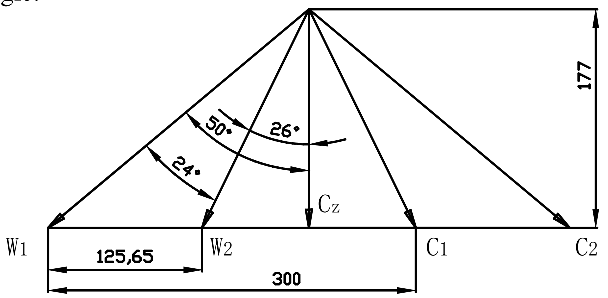


Figure 2 typical velocity triangle of axial air compressor

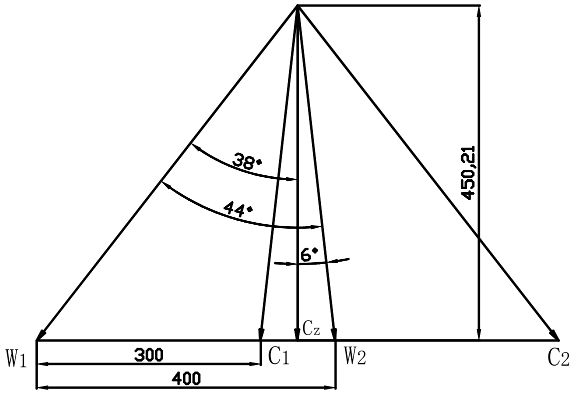


Figure 3 new velocity triangle for helium

The stage parameters of helium compressor with typical velocity triangle and new velocity triangle are shown in Table 1.

Table1 the stage parameters with typical and new velocity triangle （example）

Item	ρ	σ	$\overline{H}_{th}$	Φ	M_1	*U*	D	θ	β_1	β_2
Unit	/	/	/	/	/	m/s	/	deg	deg	deg
Air/ typical velocity triangle	0.5	1.5	0.419	0.59	0.784	300	0.4385	24	50	26
Helium/ typical velocity triangle	0.5	1.5	0.419	0.59	0.267	300	0.4385	24	50	26
helium /new velocity triangle	0.5	1.5	1.329	1.5	0.55	300	0.4385	44	38	-6

2. NEW HELIUM CASCADE PERFORMANCE WITH THE CALCULATION METHOD OF AIR CASCADE EXPERIMENTAL AND EXPERIENTIAL RULE

2.1 Calculation Method of Profile Loss

The concept of diffusion factor and the related test data applied to air typical design are used here to estimate the profile loss of new helium cascade. Diffusion factor *D* reflects the deceleration and diffusion degree toward outlet for the maximum speed of suction surface. It is expressed by inlet and outlet parameters as below:

$$D = (1 - \frac{\cos\beta_1}{\cos\beta_2}) + \frac{(\tan\beta_1 - \tan\beta_2)}{2\sigma} \cdot \cos\beta_1 \qquad (1)$$

The first item reflects the inlet and outlet velocity diffusion load, and the other one reflects the airflow turning diffusion load.

The concept of diffusion factor and the related test data are applicable for three cases: (1) when the outlet angle β_2 is a larger positive value, it is fully applicable; (2) when β_2 is a little more than zero, it is applied conceptually. While it is not clear that whether there are sufficient test data to support the conclusion; (3) when β2 is a negative value, perhaps there is no test data existed. However, for the last case, according to the calculation value of *D*, the increase of the diffusion load for airflow turning is more than the decrease of the velocity diffusion load between the inlet and outlet, so the value of *D* is increased. The result is consisted with qualitative inference. Here, Figure 149 (a) in the reference [15] is used to estimated profile losses; the higher point of the loss test curve is selected.

2.2 Calculation Method of Stage Efficiency

Stage isentropic efficiency is: $\eta_s = \frac{h_s}{h}$ (2)

h_s denotes isentropic work, *h* denotes actual work.

$$h_s = C_p(T_{2s} - T_1) = C_pT_1\left((\frac{P_2}{P_1})^{\frac{k-1}{k}} - 1 \right) \tag{3}$$

$$h = C_p(T_2 - T_1) = u\Delta C_u \text{ (Euler work)} \tag{4}$$

$$\frac{P_2}{P_1} = \frac{P_{2s} - \Delta P}{P_1} = \frac{P_{2s}}{P_1} - \frac{\Delta P}{P_1} = \pi_s - \frac{\Delta P}{P_1} \tag{5}$$

$$\pi_s = \left(1 + \frac{u\Delta C_u}{C_pT_1} \right)^{\frac{k}{k-1}} \tag{6}$$

Therefore, the stage isentropic efficiency is:

$$\eta_s = \frac{C_pT_1}{u\Delta C_u}\left\{ \left[\left(1 + \frac{u\Delta C_u}{C_pT_1} \right)^{\frac{k}{k-1}} - \frac{\Delta P}{P_1} \right]^{\frac{k-1}{k}} - 1 \right\} \tag{7}$$

The stage total pressure loss includes: ΔP_s, profile loss of blade and vane; ΔP_f, supplementary loss in the both ends of the blades. When only ΔP_s is considered, the stage isentropic efficiency can be regarded as stage profile efficiency $\eta_{profile}$.

2.3 Helium Cascade Performance and Discussion

The performance of many cases for the new stage cascade of helium compressor is calculated and the conventional case with typical air velocity triangle is also calculated. The latter can be served as a comparative reference. For the reference case, 0.9 is chosen as the stage isentropic efficiency (its profile efficiency is 0.954). The calculation conditions for all the cases are presented as follows: the tip speed is 300 m/s; degree of reaction is 0.5; solidity of blades is 1.5; the inlet total pressure is 669000*Pa*; the inlet total temperature is 310*K*; the incidence angle *i* is the minimum loss incidence defined in reference [15]. The main calculation results are summarized in Table 2, wherein the tangential velocity multiple and profile loss multiple are the ratio of them to the conventional reference value.

Table 2 Results of performance calculating for new stage and the comparison with conventional design

Item	M_1	$K_{\Delta Wu}$	D	β_1	β_2	θ	$\overline{H}_{th}$	Φ	$K_{\Delta Ps}$	$\eta_{profile}$
Unit	/	/	/	deg	deg	deg	/	/	/	/
Conventional design	0.2704	1	0.44	50.25	26.22	24	0.419	0.59	1	0.954
New stage	0.466	2.14	0.4	37.6	2.4	35.2	0.90	1.23	2.47	0.949
		2.34	0.44	39.5	0.5	39.0	0.98	1.20	2.78	0.948
		2.53	0.48	41.5	-1.4	42.9	1.06	1.16	3.05	0.947
	0.522	2.52	0.4	36.5	-1.1	37.6	1.06	1.39	3.05	0.947
		2.75	0.44	38.5	-3.2	41.7	1.15	1.35	3.46	0.945
		2.98	0.48	40.6	-5.4	46.0	1.25	1.31	3.83	0.944
	0.58	2.91	0.4	35.7	-4.1	39.8	1.22	1.54	3.68	0.945
		3.17	0.44	37.8	-6.3	44.1	1.33	1.50	4.20	0.943
		3.44	0.48	39.9	-8.6	48.5	1.44	1.46	4.67	0.942
	0.639	3.31	0.4	35.2	-6.5	41.7	1.39	1.69	4.36	0.944
		3.61	0.44	37.3	-8.8	46.1	1.51	1.65	4.99	0.941
		3.91	0.48	39.5	-11.3	50.8	1.64	1.60	5.58	0.940
	0.701	3.72	0.4	34.7	-8.6	43.3	1.56	1.84	5.06	0.943
		4.06	0.44	37.0	-11.0	48.0	1.70	1.79	5.82	0.940
		4.4	0.48	39.3	-13.6	52.9	1.84	1.74	6.55	0.939

Some conclusions can be obtained as follows:

(1) When the diffusion factor is maintained the same as that of the conventional case, the stage loading increases along with inlet Mach number increasing while the efficiency decreases along with the inlet Mach number increasing; the airflow turning angle increases along with inlet Mach number increasing while the outlet angle gradually tends to be minus value along with the inlet Mach number increasing.

(2) For the same inlet Mach number, when the tangential velocity multiple increases, diffusion factor will increase and efficiency decline.

(3) The case of higher Mach number and lower diffusion factor virtually has the same tangential velocity multiple and efficiency as the one of lower Mach number and higher diffusion factor.

3. SIMULATION OF NEW HELIUM CASCADE PERFORMANCE

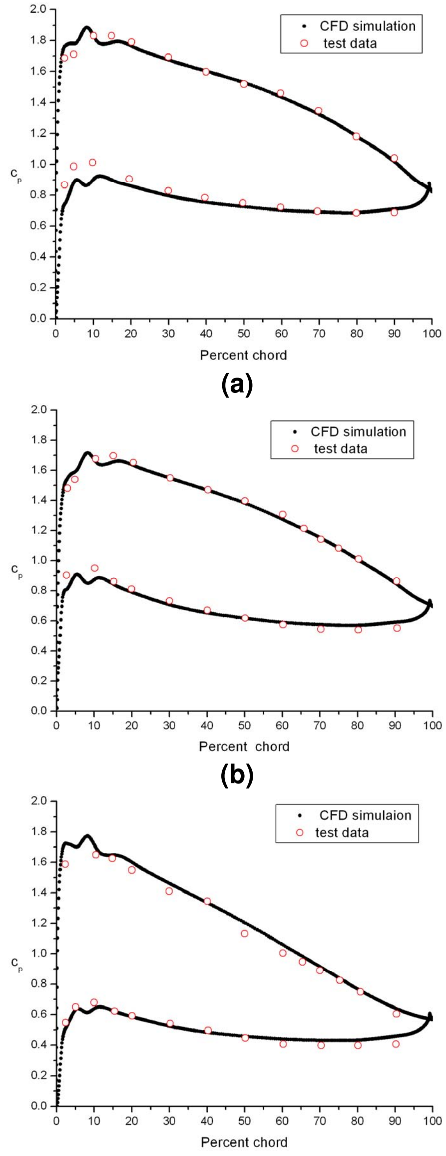
3.1 Simulation Method and Validation

Commercial CFD software, FLUENT 6.3, is used to simulate the new stage performance of helium compressor. The simulation conditions for all the cases are presented as follows: the turbulence model is Realizable k-ε[16]; the discretization format is a second order upwind model; the convergence criterion of residual is set to be 10^{-5}; the computational unstructured quadrangle mesh is generated by the preprocessor GAMBIT; only one flow passage is modeled due to the periodicity of the cascade passage flow; enhanced wall treatment is selected to model the boundary layer; the y+ of adjacent wall mesh is about 1, pressure boundary condition is used to define the fluid inlet and outlet.

It is a crucial problem that whether the result of simulation can reflect correctly the performance of new cascade. Therefore a validation is made in this paper. The method is to simulate the process of test in reference [17] with the method mentioned above and compare the simulation result with the one showed in reference [17] so as to validate the accuracy of simulation method.

The profile data for NGTE 10C4/30C50 and the test data of the typical axial-flow compressor blade sections in cascade at low speed all come from the reference [17-18]; the blade chord length b is 101.6mm; solidity of blades is 1; the experimental inlet Reynolds number is 2×10^5; no artificial boundary layer exists. Inlet velocity is 31.16m/s; turbulence intensity is 3.5%; the calculated prolonged section of inlet is $1b$, and the one of outlet is $2b$. The working substance of the validating calculation is the air, which is the same as the test. The geometric parameters calculated by the simulation method are in accordance with the test data.

Figure 4 presents the pressure coefficient distribution of blade profile surface with the inlet angle 30 °, 45 ° and 60 °. It is clearly shown that the values of simulation and test point data fit well. Because of the airflow accelerated in the front of blade, the airflow becomes instable there. Even if in a test it is very difficult to get a smooth curve. So it is a normal phenomenon. The values of turning angles from the CFD simulation results and test data are shown in Table 3. The CFD simulation results and the test data fit close. The profile losses are calculated following the method in section 2.1. The calculated results and the CFD results are shown in Table 3. The calculated results by use of experiential formulas and the CFD results match well. The former is a little bigger than the latter.



(a)

(b)

(c)

Figure 4 pressure coefficient distribution of blade section surface
(a) β_1=30°,σ=1, α=15.3°; (b) β_1=45°,σ=1,α=13.8° (c)β_1=60°,σ=1,α=15.6°

According to the series of validation and calculation showed above, it can be found that the result from simulation introduced in this paper corresponds well with the one from test data in reference [17], so that it can be used to simulate the performance of new helium cascade.

3.2 New Helium Cascade Shaping

The preliminary study on stage performance of the new velocity triangle for helium shows that the stage loading can be increased severalfold so that helium compressor pressure ratio can be increased. On the basis of this theoretical analysis, high-turning angle blades are designed. The selection principle for parameters of blade profile is as follows:

1. Original profile

By far, symmetrical airfoil profile or thin airfoil airscrew profile can be curved following some certain request to obtain the subsonic compressor profiles. The original profiles applicable for subsonic compressor cascades include British C-4, American NACA-65, Soviet Union BC-6 etc. In the range of medium subsonic speed, the original profile C-4, NACA65-010 and BC-6 have the similar thickness distribution and the aerodynamic performance. They have similar practicability. The inlet Mach number in this paper is from 0.2 to 0.7, which is in the range of medium subsonic speed. So, the British C-4 has been selected.

2. Maximum camber relative position of mean line p/b

Figure 8.7 and 8.8 in reference [19] show the experimental curve of p/b and cascade characteristic. From the figures, p/b=0.5 is appropriate in the operating range and high speed performance. Therefore, the circular mean line has been selected.

3. Maximum relative thickness d/b

From reference [20], when d/b is greater than 12.5%, the maximum lift-drag ratio of cascade will drop rapidly. The thickness distribution law of C-4 profile is selected in the paper, and the maximum thickness is the 10% of chord.

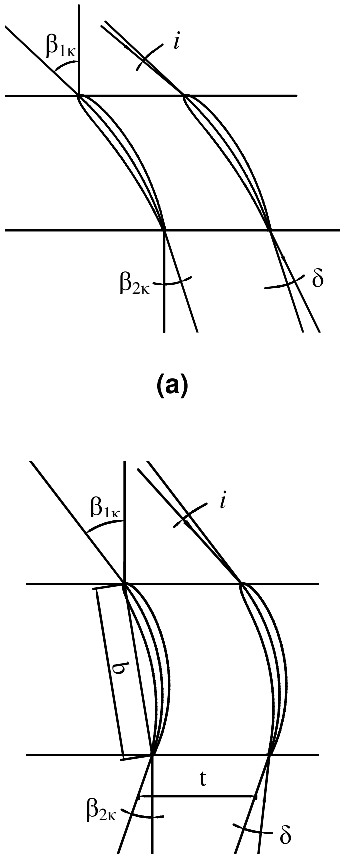
4. Cascade solidity b/t

For the compressor design, cascade solidity b/t is an important geometry parameter which reflects the influence degree of adjacent profiles. It impacts blade aerodynamic loading, and is also related with intensity and configuration. When b/t is oversize, the friction loss will be increased. When b/t is undersize, the equivalent divergence angle will be increased, and then the efficiency will be reduced. The selection of cascade solidity is also related with the working substance of engine. In the design of helium compressor, cascade solidity is 1.5 at the first stage, because the relative inlet and outlet diameter are bigger in this case. In order to be conveniently compared, cascade solidity of both conventional design and new helium cascade is 1.5.

5. Degree of reaction

When degree of reaction is 0.5, the stage of inlet and outlet velocity triangle of rotor cascade is symmetrical, and the diffusion load in rotor cascade and stator cascade is equivalent. The flow loss of such stage is smallest and the efficiency is highest. In subsonic case, when stage degree of reaction is 0.5, the bigger tip speed is permissive, and the bigger theoretical work can be obtained. Therefore, it has been extensively used in subsonic compressor that degree of reaction is 0.5. In this paper, the degree of reaction of both conventional design and new helium cascade is 0.5.

The minimum loss incidence defined in reference [15] is chosen to serve as incidence angle *i*. The new blade profile is shown in Figure 5((a) is the conventional blade profile). For all the cases, the tip speed is 300m/s, degree of reaction is 0.5, solidity of blades is 1.5, inlet chord Reynolds number is 2×10^6, the inlet total temperature is $310K$ and the inlet total pressure is $669000Pa$.



(a)

(b)

Figure 5 blade shaping
(a) conventional blade profile
(b) new blade profile

3.3 Simulation Results and Discussion

The turbulence model and computational mesh structure are the same as that of section 3.1. The simulation for conventional helium cascade case and many cases of new helium cascade stage, which can enhance pressure ratio, are simulated and the results finally summarize below:

Table 4 simulation results of the new stage performance and the conventional design

Item	M1	i	$K_{\Delta Wu}$	D	β1	β2	θ	$\overline{H}_{th}$	Φ	$\eta_{profile}$
unit	/	/ deg	/	/	deg	deg	deg	/	/	/
Conventional design	0.2704	3.1626	1	0.44	50.25	26.52	23.73	0.4066	0.58	0.946
new stage	0.466	1.9477	2.19	0.4	37.63	2.53	35.1	0.89	1.23	0.937
		1.5574	2.37	0.44	39.53	0.78	38.75	0.97	1.20	0.939
		0.9590	2.55	0.48	41.48	-0.92	42.4	1.04	1.15	0.938
	0.5223	1.7594	2.57	0.4	36.52	-1.18	37.7	1.05	1.39	0.931
		1.2222	2.80	0.44	38.52	-3.19	41.71	1.14	1.35	0.932
		0.6303	3.03	0.48	40.56	-5.45	46.01	1.24	1.31	0.933
	0.57999	1.5172	2.97	0.4	35.74	-4.26	40	1.22	1.54	0.923
		0.8064	3.28	0.44	37.81	-7.23	45.04	1.37	1.52	0.924
		0.5981	3.52	0.48	39.95	-9.18	49.13	1.45	1.46	0.927
	0.6394	1.2873	3.38	0.4	35.17	-6.92	42.09	1.39	1.69	0.912
		0.8300	3.68	0.44	37.32	-9.36	46.68	1.51	1.65	0.916
		0.2675	4.00	0.48	39.54	12.16	51.7	1.65	1.60	0.918
	0.7013	1.2591	3.84	0.4	34.73	-9.75	44.48	1.60	1.88	0.89
		0.7592	4.19	0.44	36.98	12.45	49.43	1.75	1.82	0.894
		0.1043	4.55	0.48	39.29	15.52	54.81	1.92	1.78	0.897

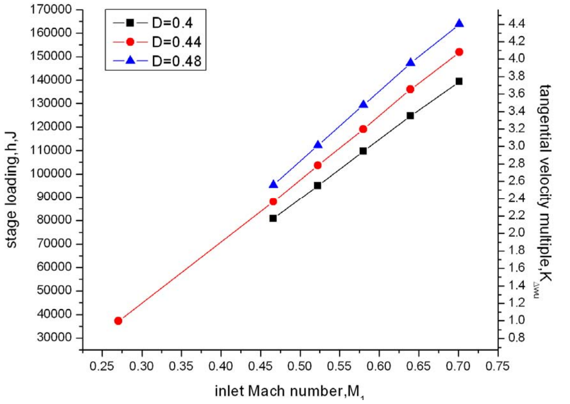


Figure 6 Variations of stage loading along with inlet number and diffusion factor

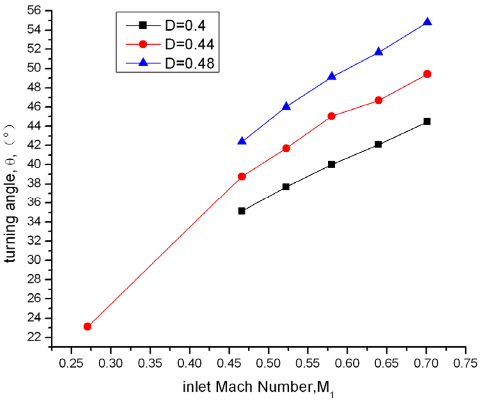


Figure 8 Variations of turning angle along with inlet Mach number and diffusion factor

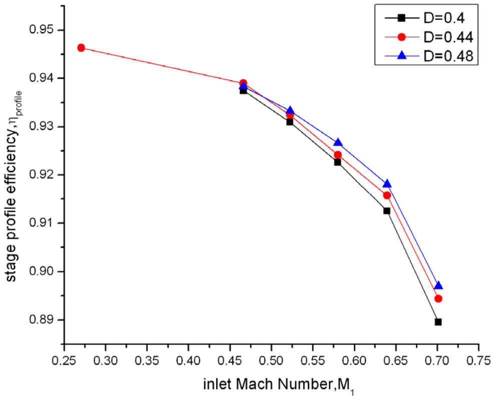


Figure 7 Variations of stage profile efficiency along with inlet Mach number and diffusion factor

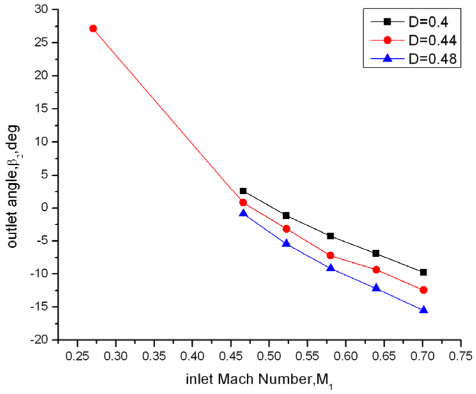


Figure 9 Variations of outlet angle along with inlet Mach number and diffusion factor

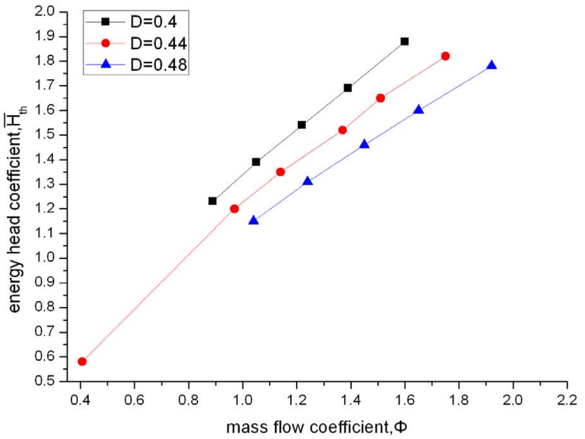


Figure 10 Variations of mass flow coefficient along with energy head coefficient and diffusion factor

Table 4 and Figure 6 through Figure 12 show that the CFD calculation results have the same variability trends as the theoretical calculation results.

From Figure 6 and Figure 7, for the same diffusion factor, the stage loading increases along with inlet Mach number increasing and the stage profile efficiency decreases along with the inlet Mach number increasing. When the diffusion factor is maintained the same as that of the conventional case, the inlet Mach number increases from 0.2704, which is calculated from the conventional case, to the new 0.466 to 0.7013. While the tangential velocity multiple reaches 2.37 to 4.19. Stage profile efficiency is declined from conventional case of 0.946 to new cases of 0.939 to 0.894.

Figure 8 and Figure 9 show that, with the same diffusion factor, the turning angle increases along with the inlet Mach number increasing and the outlet angle decreases gradually tends to be minus value along with the inlet Mach number increasing. When the diffusion factor is maintained the same as that of the conventional case, the inlet Mach number increases from the conventional case of 0.2704 to the new cases of 0.466 to 0.7013. While the turning angle reaches 38.75° to 49.43° and outlet angle reaches 0.78° to -12.45°。

From Figure 10, comparing with the conventional design, the mass flow coefficient and the energy head coefficient can be increased severalfold.

Figure 11 and Figure 12 show that, in the same inlet Mach number, the tangential velocity multiple increases along with diffusion factor increasing and the stage profile efficiency increasing.

Figure 13 shows the flow line of cascade flow field and Figure 14 shows the partial vectorgraph of cascade flow field. From these figures, there are only a few separating phenomena just in the blade trailing edge and no separating phenomenon occurs in other areas of total flow field.

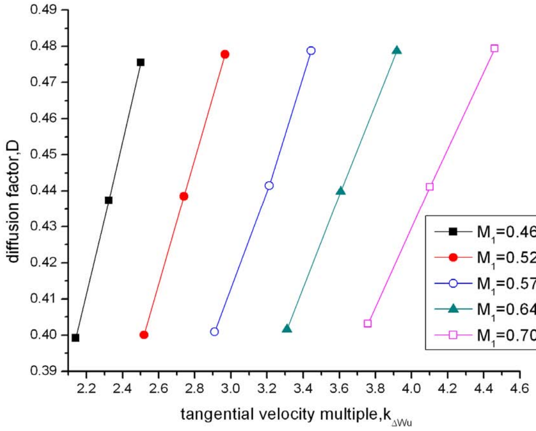


Figure 11 Variations of tangential velocity multiple along with diffusion factor

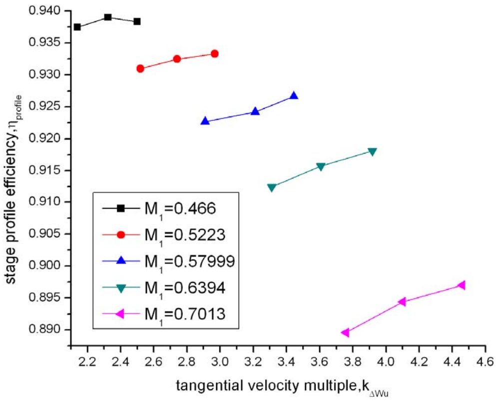
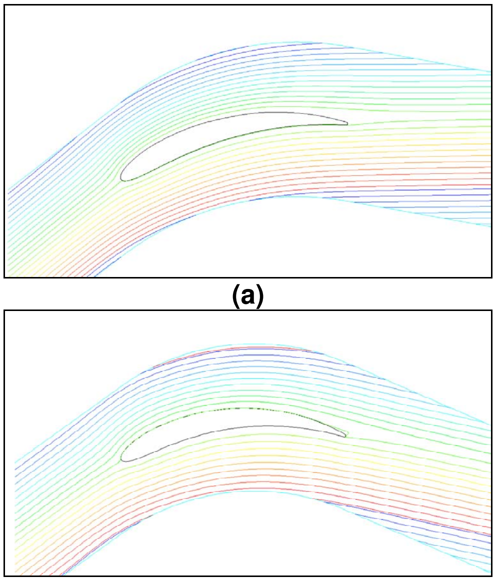


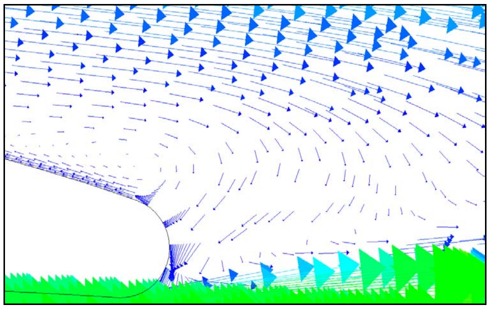
Figure 12 Variations of tangential velocity multiple along with stage profile efficiency



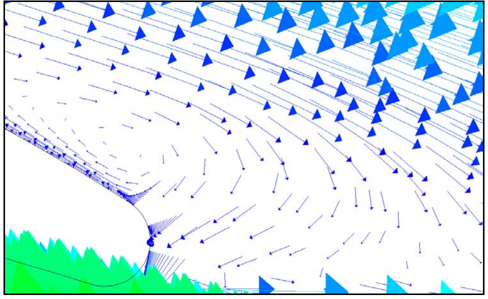
(a)

(b)

Figure 12 Flow line of cascade flow field
(a) M_1=0.466,D=0.44;(b) M_1=0.7013,D=0.44

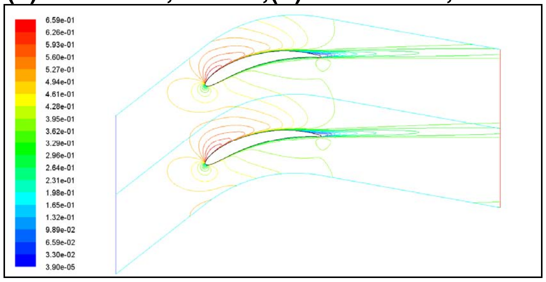


(a)

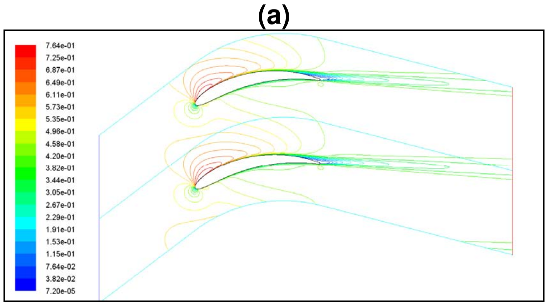


(b)

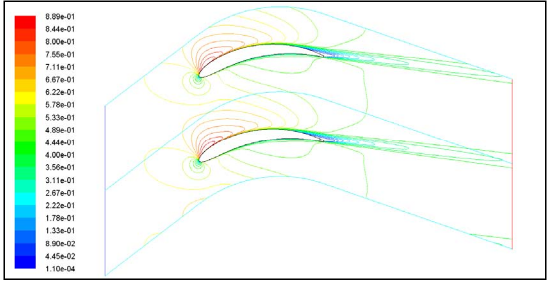
Figure 13 Partial vectorgraph of cascade flow field (a) M1=0.466,D=0.44;(b) M1=0.7013,D=0.44



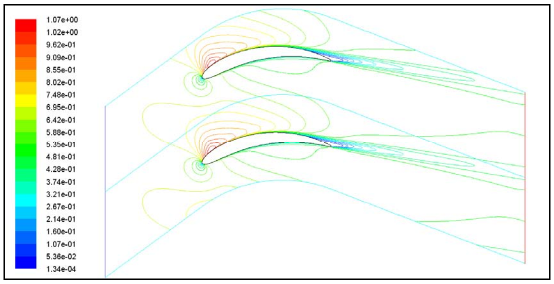
(a)



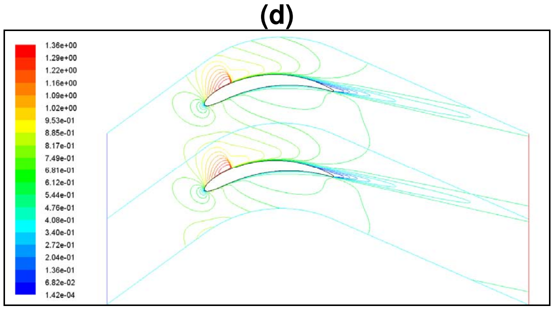
(b)



(c)



(d)



(e)

Figure 14 Mach number isoline (D=0.44) (a) M_1=0.466 $K_{\Delta Wu}$ =2.37; (b) M_1=0.5223 $K_{\Delta Wu}$ =2.80; (c)M_1=0.57999 $K_{\Delta Wu}$ =3.28; (d) M_1=0.6394 $K_{\Delta Wu}$ =3.68; (e) M_1=0.7013 $K_{\Delta Wu}$ =4.19

There are many simulation cases in this paper, so, only the situation that when diffusion factor is the same as that of the conventional design is taken as an example. The Mach number isoline (Figure 14) is showed in figure

Figure 14 shows that the whole flow field is stable. When inlet Mach number is 0.466, 0.5223 and 0.57999, the whole flow field has no transonic phenomenon. But when inlet Mach number is 0.6394 and 0.7013, there is transonic phenomenon in the whole flow field, especially when inlet Mach number is 0.7013, the suction surface exists obvious transonic phenomenon.

Using the calculation method (Table 2), for a same inlet Mach number, the efficiency decreases if the tangential velocity multiple increases. But the CFD result in Table 4 shows an increase of efficiency if tangential velocity multiple increases. The reasons for the different results are as below:

On the one hand, the theory calculation is only a way of estimation, there are some limits existing in estimation method. Firstly, the air cascade test is at low-speed, it needs experiment to validate whether the calculation method is appropriate for medium Mach number helium cascade; Secondly, the turning angle and outlet angle are different from the conventional one, the experimental data are lacking; Thirdly, the test data are not sufficient to support the correlation curve of losses and diffusion factor.

On the other hand, the cases of numerical simulation and theory estimation are limited; the present cases can not reflect the whole changing process. In Table 4, when inlet Mach number is 0.466, only three test points can show that the profile efficiency first ascend then descend but the other cases can not achieve the highest efficiency, therefore, the cases can not completely reflect the changing law of tangential velocity multiple and the stage profile efficiency.

4. CONCLUSIONS

(1) From simulation results of new helium cascade performance, it can be found that: (a) the new velocity triangle stage is suitable for helium compressor and the stage loading could be increased severalfold. Therefore the number of stage and the axial length are both reduced a lot; (b) The descend value of stage profile efficiency is not prominent when the tangential velocity multiple is 2 to 3, and stage profile efficiency is still above 0.894; (c) There is basically no separating phenomena in all flow field of new helium cascades.

(2) There are some differences between simulation results and the estimated results showed in section 2.3. The reason is that some limits exist in estimation method, that is: (a) air cascade test is at low-speed; (b) the turning angle and outlet angle are different from the conventional one. The experimental data are lacking; (c) the test data are not sufficient to support the correlation curve of losses and diffusion factor.

(3) The simulation target is the cascade based on the original c-4 thickness distribution, which is not optimized on the profile thickness distribution. For the reason of large difference between new cascade and conventional cascade, the optimization of the profile thickness distribution and shape of flow field are expected to be a greater potential for enhancing performance.

(4) 3D effects and off-design regimes will be taken into account in the future work.

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