18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18-S04-3

THE APPLICATION OF SIMILARITY CRITERIA ON HELIUM COMPRESSOR ON POWER CONVERSION SYSTEM OF HTGR-GT

Mingchen Sun
Institute of Nuclear Energy Technology, Tsinghua University
Phone: 010-62795454
E-mail: smc02@mails.tsinghua.edu.cn

Xiaoyong Yang
Institute of Nuclear Energy Technology, Tsinghua University
Phone: 010-62795454
E-mail: xy-yang@mail.tsinghua.edu.cn

Jinling Li
Institute of Nuclear Energy Technology, Tsinghua University
Phone: 010-62795454
E-mail: jlli@mail.tsinghua.edu.cn

Jie Wang
Institute of Nuclear Energy Technology, Tsinghua University
Phone: 010-62795454
E-mail: wjinet@tsinghua.edu.cn

ABSTRACT

The 10MW high temperature gas-cooled test reactor (HTGR-GT) is the first modular pebble bed reactor built in China, which needs to be researched on power conversion system. The compressors, as one key component of the system, provide the necessary helium pressure for operation in the turbine and coolant circulation throughout the reactor plant primary circuit. Their performance influences cycle efficiency of HTGR-GT power conversion system. Considering the difficulties and cost of managing compressor test using helium as working gas under the designed conditions, air is selected as working gas. Some criteria, which are suitable for the performance test of helium compressors when different working fluid are used, have been presented based on the paper review of the similarity criteria for turbomachine design and management. Reynolds numbers are both larger than 3×10^5 and Mach numbers are both less than 0.6 no matter the working gas is helium or air. In this case, only keeping ratio between mass flow rate and rotating speed the same, the flow of air in the compressor will be similar with the flow of helium. This paper uses the selected similarity criteria to predict the running condition for HTGR-GT helium compressors using air working gas. The rotating speed is 5540r/min in designed load, and in partial loads rotating speed will be shown in the compressor map. The experimental conditions including pressure, temperature, rotating speed and mass flow rate are given in this paper.

Key words: similarity theory; compressor; dimensionless criteria; HTGR

1. INTRODUCTION

The high temperature gas-cooled reactor (HTGR) coupled with the gas turbine cycle is considered as one of the leading candidate concepts for future nuclear power development [1]. Helium gas turbine direct cycle (Brayton cycle) has many advantages, such as high electricity efficiency, simple system, high safety, high economy and so on [2]. But there are still many difficulties in technology and theory to overcome in the helium gas turbine direct cycle.

Axial flow compressor using helium gas as working fluid is one of the key parts in the Brayton cycle, which performance has a direct effect on the whole cycle efficiency. The aerodynamics of the helium gas compressor can not only calibrate the flow of the primary circuit coolant but also supply the theory foundation for the match between the helium gas turbo machine and HTGR. So it is necessary to make a deep study and a theory analysis on aerodynamics of the helium gas compressor. Considering the difficulty of conducting performance tests of helium gas compressor, air is selected as the working fluid instead of helium gas. The physical property differences between air and helium gas make it difficult to convert the pneumatic parameters under the helium gas condition to that under the air condition and this problem hasn't been solved perfectly so far [3]. In this paper, several decisive similarity criteria are conducted and analyzed based on the similarity theory when different gases are used. The low Reynolds number which affects the compressors' pneumatic performance and stability is analyzed. The test parameters of the compressors (HTGR-GT) are determined in theory which can supply theory foundation for performance test and optimization of the compressor.

2. THE SELECTION OF THE DECISIVE CRITERIA FOR AXIAL COMPRESSOR

The flow in the axial compressor is very complicated three-dimensional and compressible. So it is very difficult to get the similarity criteria through the simple analytic equation. In this part, dimensional analytic method is used to get the decisive similarity of axial compressor.

For building study model compressor should be simplified as following:

(1) The flow in axial compressor is axisymmetric, one-dimensional, stable and compressible.

(2) There is no heat exchange between inside and outside of compressor and there is also no heat exchange within the flow field.

(3) The adiabatic exponent, specific heat and dynamic viscosity of working fluid (helium and air) don't change with the temperature.

(4) Gravity of the gas is ignored.

(5) Dimension of the model is the same as that of the prototype.

For finding the necessary and sufficient condition of dynamics and kinetic similarity for the flow in compressor, the parameters of the compressors should be determined. These parameters include pressure P, temperature T, adiabatic exponent K, gas constant R, mass flux G_m, dynamic viscosity μ, rotate speed n and characteristic dimension D, which determine all of the characteristic parameters of the compressor such as efficiency η, pressure ratio π and load factor H , etc.

For conveniences of deduction, acceleration of gravity g, efficiency η and pressure ratio π is added into these parameters. Four basic dimensions are selected: Length L, Mass M, Temperature θ and Time T. The dimension of the parameters is presented as following Table 1.

There are nine main parameters and four dimensions, so according to similarity theory there are 9-4=5 dimensionless groups.

The objects need to be studied are efficiency η and pressure ratio π which are the function of other parameters, as is shown in function Eq. (1) and (2).

$$\pi = f_1(p,\ T,\ m,\ R,\ k,\ \mu,\ n,\ D,\ g) \tag{1}$$

$$\eta = f_2(p,\ T,\ m,\ R,\ k,\ \mu,\ n,\ D,\ g) \tag{2}$$

Eq. (1) can be described as dimensionless Eq. (3).

$$[\pi] \equiv [p^{x_1},\ T^{x_2},\ m^{x_3},\ R^{x_4},\ k^{x_5},\ \mu^{x_6},\ n^{x_7},\ D^{x_8},\ g^{x_9}] \tag{3}$$

Then we can get dimensional Eq. (4) as following:

$$[(\frac{M}{LT^2})^{x_1}\theta^{x_2}(\frac{M}{T})^{x_3}(\frac{L}{\theta})^{x_4}(1)^{x_5}(\frac{M}{LT})^{x_6}(\frac{1}{T})^{x_7}(L)^{x_8}(\frac{L}{T^2})^{x_9}] \equiv [M^0L^0T^0\theta^0] \tag{4}$$

Four dimension equations are got, as is shown in equation set 5.

$$\begin{cases} x_1 + x_3 + x_6 = 0 \\ -2x_1 - x_3 - x_6 - 2x_9 = 0 \\ -x_1 + x_4 - x_6 + x_8 + x_9 = 0 \\ x_2 - x_4 = 0 \end{cases} \quad (5)$$

Eq. (5) have nine variable parameters but there are only four equations, so there are five parameters can be selected freely. Dimensionless group can be solved by trial-and-error method [4]. For example, let $x_1 = 1$, $x_2 = -1$, $x_7 = 1$, $x_3 = 0$, then the solution of other unknown parameters in the Eq. (5) is $x_4 = -1$, $x_6 = -1$, $x_9 = 1$, $x_8 = 2$.

Table 1 Dimension of the parameters

Parameters	Name	Dimension			
		Length[L]	Mass[M]	Temperature[Θ]	Time[T]
p	Pressure	-1	1	0	-2
T	Temperature	0	0	1	0
G_m	Mass Flux	0	1	0	-1
g	acceleration of gravity	1	0	0	-2
μ	dynamic viscosity	-1	1	0	-1
n	rotate speed	0	0	0	0
D	characteristic dimension	1	0	0	0
η_k^*	efficiency	0	0	0	0
π	pressure ratio	0	0	0	0
R	Gas constant	1	0	-1	0
K	Adiabatic exponent	0	0	0	0

Then we get one similarity criterion of the Reynolds number

$$\pi_1 = \frac{pnD^2}{TgR\mu} = \frac{U\rho RTD}{TRg\mu} = \frac{\rho UD}{g\mu} \propto \mathrm{Re}.$$

Other dimensionless group can be got by method trial-and error as follow:

Flux coefficient $\pi_2 = \varphi = \frac{c}{U}$

Axial direction Mach number $\pi_3 = \frac{w_1}{\sqrt{kgRT}} = M_w$

Rotational Mach number $\pi_4 = \frac{U}{\sqrt{kgRT}} = M_U$

Load factor $\pi_5 = \psi = \frac{H}{U^2}$.

Because the ratio of axial direction Mach number and Rotational Mach number is Flux coefficient, only two of those dimensionless numbers such as Rotational Mach number and Flow coefficient can be selected for the decisive similarity criteria.

Because of the difference of the adiabatic exponent *k*, the performance of compressor is different when experiments are performed with air or helium gas. So it is another important decisive similarity criterion.

In conclusion, Flux coefficient, Rotational Mach number, Load factor and Reynolds number can be selected as the decisive similarity criteria.

3. ANALYSIS OF THE DECISIVE SIMILARITY CRITERIA

3.1 Reynolds number

Reynolds number can be comprehended as a comparative measure of inertial and viscous (diffusive) effects within the flow field. To achieve dynamic similarity in two different flow situations, the Reynolds numbers must both be identical. But when Reynolds number is more than 2.5×10^5[5], it has little effect on the dynamic similarity and so it can be ignored. The experimental research on whole compressor performance characteristic shows that the flow loss will increase and flow condition on blade profile will get worse when the chord Reynolds number is less than the critical Reynolds number. The adverse influences on compressor performance caused by reduction of Reynolds number will rise when several stages disadjust inside of multi-stages compressor. It is especially obvious in operation of compressors at partial load when reduced rotational speed of compressors is decreased. Experimental data showed that when chord Reynolds number reduces from 3.5×10^5 to 1×10^5, compressor efficiency decreased about 4% at 1.0 working condition and about 6% at 0.8 working condition as shown in Figure 1 [6]; the compressor flow rate decreased about 6% at 1.0 working condition and about 12% at 0.8 working condition as shown in Figure 2 [6].

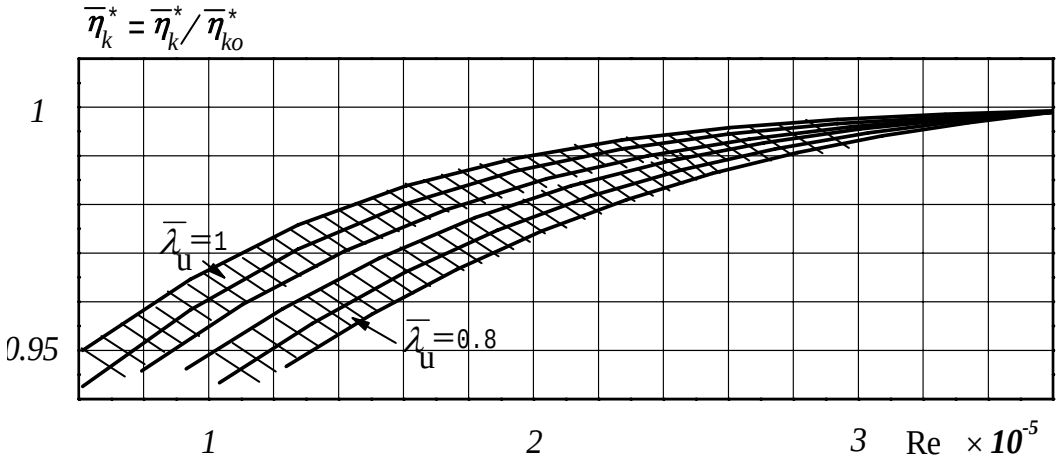

Figure. 1. Compressor efficiencies changed with chord Reynolds number

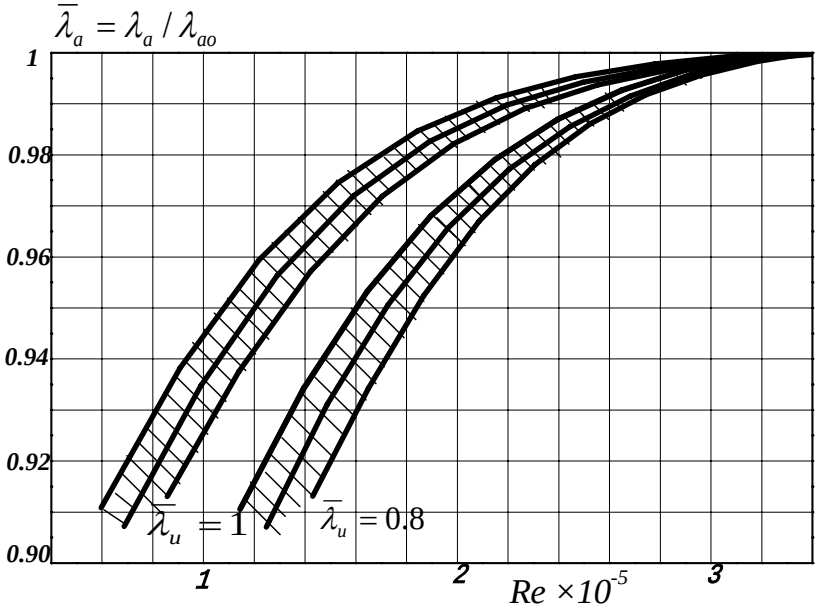

Figure. 2. Flow coefficient of compressor changed with chord Reynolds number

The effect of the low Reynolds number to compressor is shown as following Figure 3.

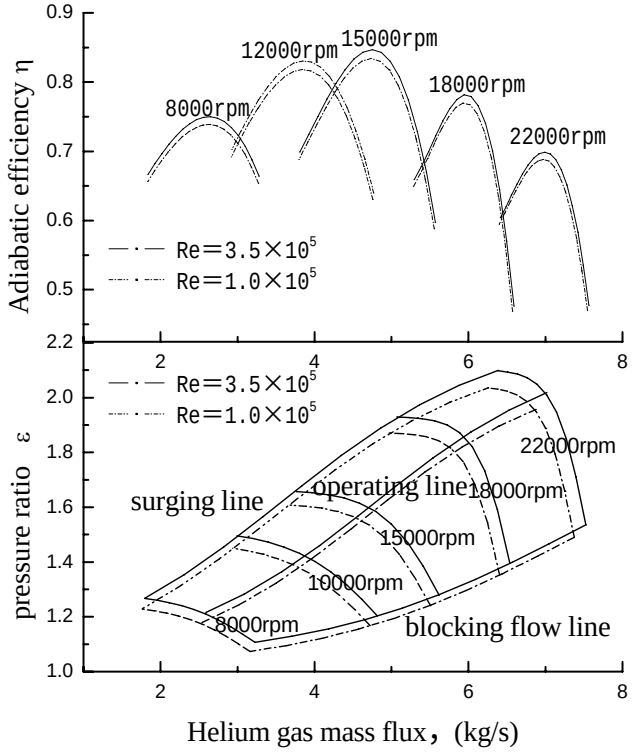

Figure 3 Performance map of the helium gas compressor in different Reynolds numbers

3.2 Flux coefficient and Load factor

Velocity triangle of the gas flux in compressor can be determined by the Reaction degree, Flux coefficient and Load factor. Reaction degree is the inherent parameter of compressor and it can keep the same for model and prototype if they are similar in geometry. So when Flux coefficient and Load factor in the model equal to those in the prototype, dimensionless velocity triangles in the model are similar to those in the prototype. The relationship between the velocity triangle and Flux coefficient and Load factor can be described as following Figure 4.

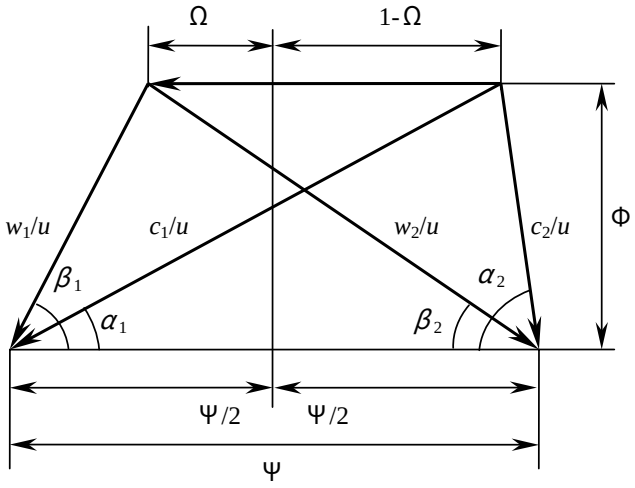

Figure 4 Dimensionless velocity triangle

3.3 Mach number and adiabatic exponent *k*

Mach number and adiabatic exponent *k* are the key factors describing the flow condensability. When using the same working fluid to do experiment, adiabatic exponent *k* and Mach number of model are the same as that of prototype. But when using different working fluid because of the difference of adiabatic exponent *k*, the flow is different and so similarity between the model and the prototype may be destroyed. The flow in compressor is very complicated so we can only analyze the flow in adjust stage of compressor.

Through deduction, the following equation is got by Mass equation, aerodynamic function and gas equation of state.

$$\frac{\Delta F}{F} = -\frac{\Delta c}{c} + \frac{\Delta c^2}{2c^2} M^2 [1 + \frac{k-1}{2} M^2 + (\frac{k-1}{2})^2 M^4 + \cdots\cdots]^{[7]} \quad (7)$$

Where *F* is acreage of cross section; *c* is the local velocity; *M* is local Mach number and *k* is adiabatic exponent.

Let $X = M^2[1 + \frac{k-1}{2} M^2 + (\frac{k-1}{2})^2 M^4 + \cdots\cdots]$

When Mach number is selected as the decisive similarity criterion, the value of *X* in experiment is named X_M; when Euler number is selected as the decisive similarity criterion, the value of *X* in experiment is named X_E; the value of *X* in prototype is named X_P.

So the D-value of the X_P -X_M and X_E -X_M can be got when the working fluid in prototype is helium and in model is air, as shown in Figure 5.

Figure 5 shows the D-value of *X* changes with Mach number. When Mach number is less than 0.4, the D-value of X_P -X_M is only 0.01 and far less than the value of X_E -X_M. So in this range adiabatic exponent has almost no influence on the similarity.

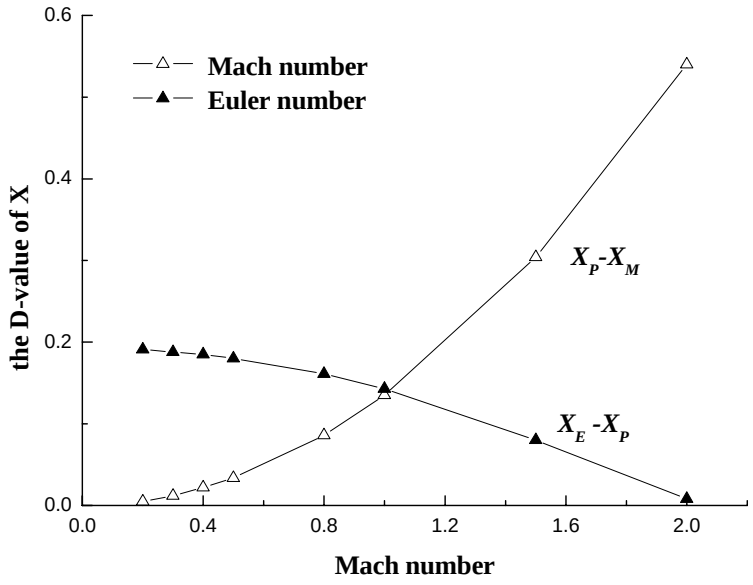

Figure 5 The D-value of X changes with Mach number

4. THEORY ANALYSES OF PERFORMANCE PARAMETERS FOR HELIUM GAS COMPRESSOR USING AIR AS WORKING FLUID

Before doing the experiment using air as working fluid, appropriate decisive similarity criteria must be selected to determine the experimental parameters based on design working conditions. Because design Mach number of helium gas compressor is less than 0.5, adiabatic exponent and Mach number have little influence on the performance experiment. Based on the geometry similarity, the kinematics similarity can be guaranteed just keeping flux coefficient and Load factor of the model as same as those of the prototype, then the flow similarity is achieved.

4.1 The selection of the experiment condition

Experimental parameters include inlet temperature, inlet pressure, Mass flux and rotate speed.

Inlet temperature: There is no restriction on inlet temperature. But for convenience, let inlet temperature of

the model the same as that of the prototype $T_M=T_P$。

Inlet pressure: To keep the Reynolds number of the model as same as that of the prototype, inlet pressure of design condition should be about 2.3×10^5Pa.

Rotate speed: Because $(\psi_{pol})_M=(\psi_{pol})_P$、 $u=n\pi D$ and $h_{pol}=mRT(\varepsilon^{(k-1)/k}-1)/(m-1)$, we can get rotate speed expression as shown Table 2.

Mass flux: Volume flux is in direct proportion to rotate speed $n_P/Q_P=n_M/Q_M$， then we can get Mass flux expression as shown Table 2.

Table 2 Air condition converse expression

Parameter	Design performance parameters	Air condition converse expression
Volume flux	Q_P	$\frac{Q_P m_l^3 n_M}{n_P}$
Power	N_P	$m_l^5 N_P(\frac{n_M}{n_P})^3 \frac{p_M}{p_P}$
Rotate speed	n_P	$\frac{n_P}{m_l}\sqrt{\frac{\frac{m_M}{m_M-1}R_M T_M[\varepsilon_m^{\frac{m_M}{m_M-1}}-1]}{\frac{m_P}{m_P-1}R_p T_p[\varepsilon_p^{\frac{m_P}{m_P-1}}-1]}}$
Pressure ration	ε_P	$\varepsilon_P^{\frac{m_M}{m_p}}$
Efficiency	$(\eta_P)_{pol}$	$(\eta_P)_{pol}$

So we can get Air experimental parameters in design condition as following Table 3.

Table 3 Air experimental parameters

performance parameters	Design condition	Air experimental parameters
G / kg/s	4.76	6.85
N / MW	1.765	0.03
n / rpm	15000	5526
ε	1.58	1.47
η_{pol} / %	85	85

4.2 Theory experimental performance map

In the same way partial load point's parameters can be calculated, which can form compressor performance map under air condition. The effect of Reynolds number (about 1×10^5) is analyzed, as shown in Figure 5.

However because of frictional secondary flow and boundary-layer separation in helium gas compressor, the results of compressor parameters conversion need to be examined by experiments.

5. CONCLUSIONS

1. The differences of working fluid physical property lead to similarity error, and the similarity error magnitude is determined by Mach number and adiabatic exponent. When Mach number is less than 0.5, it is in self-similarity zone, the adiabatic exponent of working gas has little influence and it can be ignored. Only kinematics similarity can guarantee similarity between the model and the prototype. When Mach number is more than 0.5, the influence of adiabatic exponent can not be ignored.
2. Design Mach number of helium gas compressor is about 0.3 and the error in the experiment caused by adiabatic exponent k and Mach number M is about 1%. Based on the geometry similarity, the flow similarity in the model and the prototype can be guaranteed just by keeping flux coefficient and load factor in the model as same as those in the prototype.
3. When the chord Reynolds number is less than the critical Reynolds number, the flow loss will increase and

flow condition on blade profile will get worse so that the efficiency and pressure ratio are reduced, especially in start-stop mode of the helium gas compressor.

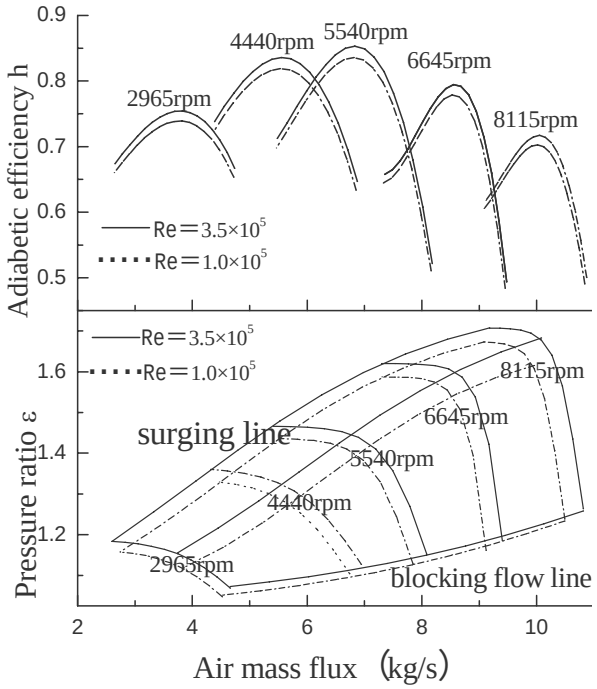

Figure 6 helium gas compressor performance map using air

ACKNOWLEDGEMENT

This research was supported by Chinese Nature Science Fund (90410001).

REFERENCES

[1] Brey H L. *Historical background and future development of the high temperature gas cooled reactor. In proceedings of Seminar on HTGR Application and Development*, Beijing, January, 2001.
[2] Scheleicher R, Raffray A R, Wong C P. *An assessment of the brayton cycle for high performance power plants. In 14th Topical Meeting on the Technology of Fussion Energy.* Parkcity, Utab, USA, Oct, 15~19, 2001
[3] Liqiang Liu, Chunzheng Chen. An Evaluation of the Method of Similarity Modelling Tests Using on Turbomachines. CRYOGENICS, 1996,4（4）：43~46
[4] Zixiang Zou. The Application of of the Method of Similarity Modelling Tests Using on Turbomachines. Science publishing company, 1984（79～88）
[5] Moyes, S J, Pennington W A. *The influence of Size on the Performance of Turbo-Jet engine. 3rd Anglo-American Aeronuatical Conference*, Royal Aeronautical Society: London, 1951
[6] Ю., А., ЛИТВИНОВ, et al., ХАРАКТЕРИСТИКИ И ЭКСПЛУ АТАЦПОННЫЕ СВОЙСТВА АВИАЦИОННЫХ ТУРБОРЕАКТИВНЫХ ДБИГАТЕЛЕЙ. National Defense Industry Press, 1986
[7] Baoshan Ma, Zhuocheng Zhang. The Theory of Turbomachines. Mechanism publishing company, 1970. 375~393

