Numerical Study of the Performance Effect of Varying Vaneless Space in He Turboexpander Nozzles

Y R Meng[1,2,3]**, L Y Xiong**[1,2,*]**, L Q Liu**[1,2]**, N Peng**[1,2]**, C L Ke**[1,2,3]**, K R Li**[1,2,3]**, H R Wang**[1,2,3]

[1]Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry，Chinese Academy of Sciences, Beijing 100190, China
[2]State Key Laboratory of Technologies in Space Cryogenic Propellants, Beijing 100190, China
[3]University of Chinese Academy of Sciences, Beijing 100190, China

[*]E-mail: lyxiong@mail.ipc.ac.cn

Abstract. A numerical analysis has been carried out on a 16 mm tip diameter radial-axial flow cryogenic turboexpander using He, in order to directly compare performance characteristics by varying the vaneless space. A reference nozzle with radial clearance 0.1 mm was used in the helium liquefaction system, and six other nozzles were designed with radial clearance of 0.3 mm, 0.5 mm, 0.8 mm, 1.0 mm and 1.5 mm. As part of the design process a series of CFD simulations were carried out in order to guide design iterations towards achieving a matched flow capacity for each design. In this way the variations in the stage efficiency could be attributed to the different vaneless space only, thus allowing direct comparisons to be made. The variation in computed efficiency was used to recommend optimum value of the ratio of the nozzle vane trailing edge radius to the rotor leading edge radius (R_{te}/r_{le}).

1. Introduction

Turboexpander is one of the key components in a helium liquefier and refrigerator. The vaneless space parameter is an important variable in turboexpander design and is conventionally defined as the ratio of the nozzle vane trailing edge radius to the rotor leading edge radius R_{te}/r_{le}. Some researchers had taken up the studies on the effects of the value of R_{te}/r_{le} on turboexpanders performance.

Tunakov [1] reported an investigation into the effects of the vaneless space in radial inflow turbines in 1960. He argued that an optimum radial clearance value should exist and this should represent the best compromise between the level of flow irregularity entering the rotor and the frictional losses incurred in the vaneless space. Then he presented an empirical relationship of it

$$\Delta r / (b_2 \sin \alpha_2) \approx 2 \qquad\qquad (1)$$

Where Δr is the radial clearance, $\Delta r = R_{te} - r_{le}$, b_2 is the height of nozzle vane, and α_2 is the mean exit flow angle of nozzle.

Watanabe et al. [2] conducted experiments on a series of straight nozzle vanes giving varying radial clearance values of 3 mm, 5 mm, 10 mm, and 15 mm with a common 200mm tip diameter impeller. The configurations of nozzle vanes were selected to yield equal nozzle exit velocity $C_2 = 238.3$ m/s and equal nozzle exit flow angle $\alpha_2 = 18°40'$ at the design flow condition, which were achieved by varying the thickness of the vanes. They found that the highest turbine efficiency occurred at $\Delta r = 10$ mm. Since the nozzle vane height b_2 is 14.0 mm, $\Delta r / (b_2 \sin \alpha_2) = 2.2$. Watanabe's experimental results compared well with Tunakov's expression.

Simpson et al. [3] carried out a series of CFD simulations and an experimental program on a 135 mm tip diameter turbine using a series with different R_{te}/r_{le} ratios. They found the aerodynamic optimum value of R_{te}/r_{le} is 1.175.

If the radial clearance is too small, although the friction loss is reduced, the jets and wakes do not mix out to the same extent, resulting in a higher level of flow non-uniformity in the rotor inlet. In addition to influencing aerodynamic performance, the flow irregularity also has an influence up on the structural behavior of the rotor, introducing an alternate loading pattern as the blades pass through successive jets and wakes. According to Li's introduction, when the R_{te}/r_{le} value of 1.04 was increased to 1.16, the noise would be from 120 dB to 110 dB [4]. To the contrary, with larger radial vaneless space between the nozzle vane trailing edge and the rotor leading edge, additional frictional loss incurs due to the longer flow path, though the flow uniformity can be guaranteed. These results involved large radial turbines, but characteristics of turbines may vary with scale. There is little information available regarding the optimum vaneless space for cryogenic micro-turboexpander. This investigation focuses on the vaneless space parameter in cryogenic turboexpander nozzle design with the aim of ascertaining the effects of varying the radial clearance parameter on turbine stage performance. This was achieved by carrying out computational fluid dynamics (CFD) calculations to guide the nozzle vane geometry design with varying value of the vaneless space parameter R_{te}/r_{le}. Performance comparisons were carried out under design condition to ascertain the resulting variations in turbine stage efficiency.

2. Nozzle Vane Design Procedure
The design conditions are presented in Table 1.

Table 1. The design condition

Working medium	q_m (kg·s^{-1})	P_{01} (Pa)	T_{01} (K)	P_3 (Pa)	N (r·min^{-1})
He	0.02106	1000000	45.05	610000	221736

The series of nozzles were each designed as part of a He turboexpander stage with a 16mm tip diameter rotor. The profile comprised of straight line segments and circle arcs to ensure a continuously accelerating flow throughout the vane passages. Initially, a reference vane profile was generated based on an existing design having 21 vanes with radial clearance 0.1mm, i.e., R_{te}/r_{le} ratio of 1.0125. The

nozzle is used in the helium liquidation system, because it is hypothesized that smaller the radial clearance, higher is the efficiency.
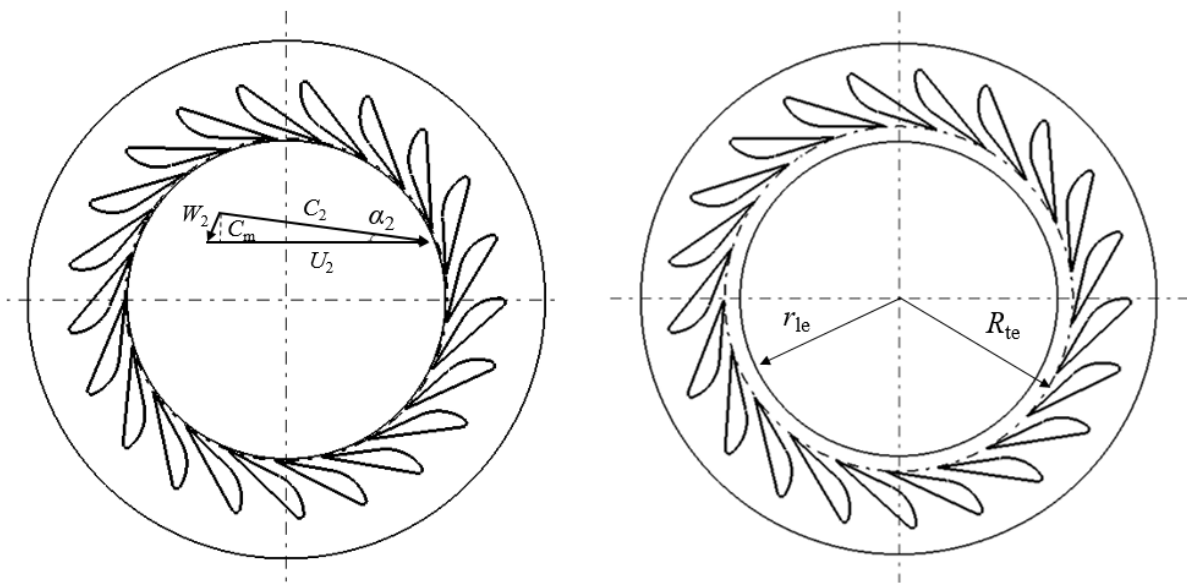
To study the effects of varying radial clearances between nozzle and rotor on performance characteristics, a further series of nozzle vanes were designed with radial clearance of 0.3mm, 0.5mm, 0.8mm, 1.0mm, 1.2mm and 1.5mm, i.e., R_{te}/r_{le} ratio of 1.0375, 1.0625, 1.1, 1.125, 1.15 and 1.1875. The nozzle vane exit blade angles were set the same value of 14° for all designs, i.e., $\alpha_{b2} = 14$°. In this condition, the flow angles at the nozzle vanes exit α_2 were close to 14°. So the design constraint placed on each design was that the mass flow capacity of turbine stage must be matched. Only by achieving this, meaningful direct comparisons could be carried out on the effect that each design had on the stage performance. To achieve this, an iterative design approach was taken using blade generation software to generate vane models and then employing CFD to guide design modifications. At first, the throat areas were set to be equal for each design, and CFD calculations were carried out to determine the resulting mass flow rates. Then the throat areas were iteratively adjusted in order to achieve the matching mass flow rates, using CFD results to guide making adjustments to the nozzle vane thickness. Typically, matching mass flow rates were achieved within 2 or 3 design iterations. In this case, the design with a larger radial clearance required an increase in the throat area in order to achieve consistent mass flow rates. The resulting profiles for the stage having R_{te}/r_{le} ratio of 1.0125 and 1.1 are presented in Figure 1. A more detailed description of the resulting designs are presented in Table 2. From the Table 2 and Appendix, the variations in the rotor inlet α_2' covers a small range of -0.17° ~ 0.27°, so the velocity triangles at the rotor inlet could be basically consistent to eliminate the efficiency degradation/upgradation caused by the impeller that would reflect as stage efficiency change.

3. Performance variation with varying with radial clearance

In the computation process, boundary condition at the stage inlet and exit are set to the operation conditions on the design point which is shown in Table 1. In order to decide the number of grids for nozzle and rotor passage without grid dependence, it is calculated whether the isentropic efficiency is stable or not according to the various grid numbers for a design. For the design with $R_{te}/r_{le} = 1.1$, three CFD computations were carried on while grid numbers were set 650k, 910k and 1,310k nodes. The variations of calculated efficiency are less than 0.05%. Since the boundary layers were expected to be relatively thin both at the vane inlet and throughout the nozzle passages, care was taken to provide sufficient grid resolution on the hub, blade and shroud surfaces with expansion ratios of approximately 1.2 applied at solid boundaries. Based on the above requirements, the grid of the order of 450k nodes per nozzle passage and 460k nodes per rotor passage was considered to be sufficient to capture the boundary layer growth for each of the vane designs. The grids used and the model set up for the nozzle with $R_{te}/r_{le} = 1.1$ build are presented in Figure 2.

The calculated mass flow rate values with different vaneless space are presented in Figure 3, which have been nondimensionalized by dividing by the design mass flow rate value. The results demonstrate that the mass flow rates were successfully matched for this nozzle series, with the variation from the design mass flow rate to be -0.6% ~ 0.3% at design point. This ensure the results of the CFD predictions to be reliable in guiding the designs towards matching flow capacities. So the meaningful direct comparisons could be carried out on the effect that each design had on the stage performance.

At the design point the variation of simulated efficiency with varying R_{te}/r_{le} value is presented in Figure 4, with the corresponding variation in the corrected mass flow rate given in Figure 3. It indicates that varying the R_{te}/r_{le} value has a significant effect on stage efficiency, particularly in the small R_{te}/r_{le} value. The efficiency of reference design with $R_{te}/r_{le} = 1.0125$ (vaneless space value of 0.1mm) is the lowest. At the design point the variation in efficiency between the seven designs ($R_{te}/r_{le} = 1.0125$ ~1.1875) covers a range of 1.5%. The results suggest that an aerodynamic optimum lies in the R_{te}/r_{le} of 1.125 which is in the range of 1.08 ~ 1.16 recommended by Li. et. al. [4]. The value is higher than the

(a) radial clearance 0.1 mm ($R_{te}/r_{le} = 1.0125$)   (b) radial clearance 1.0 mm ($R_{te}/r_{le} = 1.1$)

Figure 1. The velocity triangle at the nozzle exit and the result nozzles ring

Table 2. Resulting nozzle vane design parameters

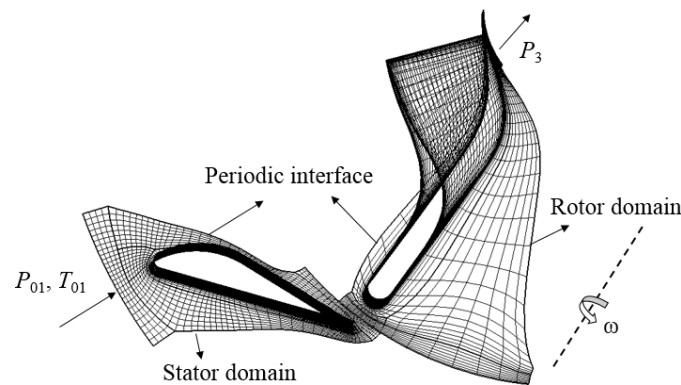| Radial clearance (mm)	R_{te}/r_{le}	PCD_{inlet} (mm)	PCD_{outlet} (mm)	σ (mm^2)	α_{b2} (deg)	α_2' (deg)
0.1	1.0125	22	16.2	0.5310	14	14.27
0.3	1.0375	22.4	16.6	0.5364	14	14.06
0.5	1.0625	22.8	17	0.5490	14	14
0.8	1.1	23.4	17.6	0.5616	14	13.83
1.0	1.125	23.8	18	0.5778	14	13.89
1.2	1.15	24.2	18.4	0.5895	14	13.76
1.5	1.1875	24.8	19	0.6075	14	13.97

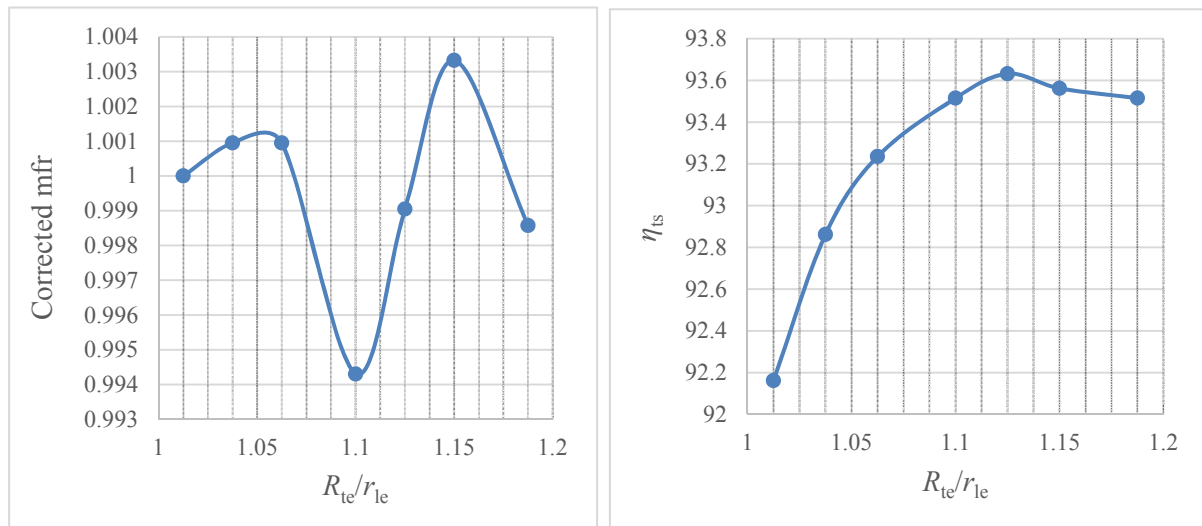**Figure 2.** Grid used for CFD calculation: nozzle ($R_{te}/r_{le} = 1.1$)

Figure 3. Corrected mass flow rate with varying R_{te}/r_{le}

Figure 4. Efficiency (total-static) with varying R_{te}/r_{le}

optimum value of 1.0544 previously recommended by Watanabe et al. [2], and lower than the optimum value of 1.175 presented by Simpson [3] based on the numerical and experimental results. As the value of R_{te}/r_{le} is increased, there is a general trend towards larger variation of the efficiency in the small value range, smaller variation of the efficiency in the large value range. No significant variation in efficiency was recorded between nozzles with R_{te}/r_{le} value of 1.1~1.1875. It means that the turbine stage efficiency isn't sensitive when the R_{te}/r_{le} values are in this large range. And it indicates that varying the R_{te}/r_{le} value of 1.1~1.1875 does not have as significant an impact on stage efficiency as varying the R_{te}/r_{le} value of 1.0125~1.1. The efficiency had only a bit drop, although additional frictional loss occurred as the flow accelerated over a longer distance from nozzle vane throat to rotor inlet. This suggests the friction loss in the vaneless region comprises only a small part of the total loss, compared with the irregularity loss.

The static pressure distributions in the midspan surface of the turbine with the R_{te}/r_{le} values of 1.0125 and 1.125, as showed in Figure 5. The pressure distribution is non uniform in the vaneless space

of the reference design, and a high pressure zone occurs in the upstream of the rotor leading edge. By contrast, at the optimum efficiency design condition, the pressure distribution is uniform in the upstream of the rotor leading edge. As shown in Figure 6, circumferential distributions of the static pressure in the rotor inlet are similar to the static pressure distributions in the midspan surface. These results provide further evidence to support the performance variation with different radial clearance.
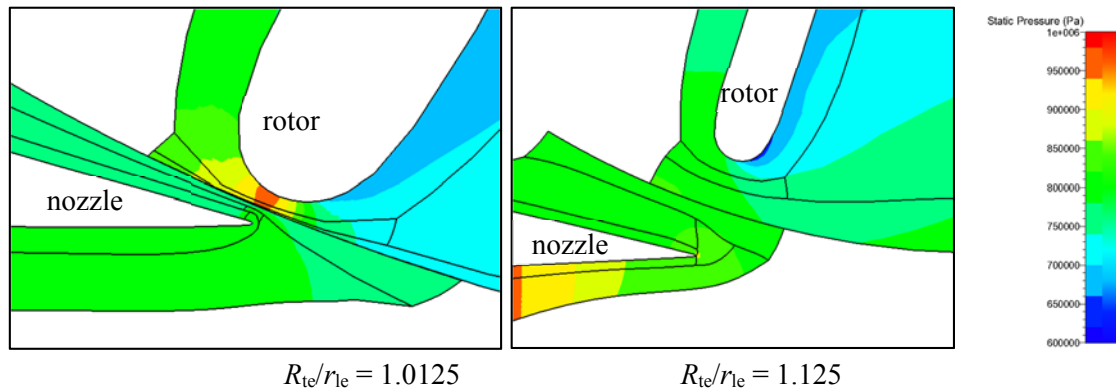

$R_{te}/r_{le} = 1.0125$ $R_{te}/r_{le} = 1.125$

Figure 5. The static pressure distribution in the midspan surface

$R_{te}/r_{le} = 1.0125$ $R_{te}/r_{le} = 1.0375$ $R_{te}/r_{le} = 1.0625$ $R_{te}/r_{le} = 1.1$

$R_{te}/r_{le} = 1.125$ $R_{te}/r_{le} = 1.15$ $R_{te}/r_{le} = 1.1875$
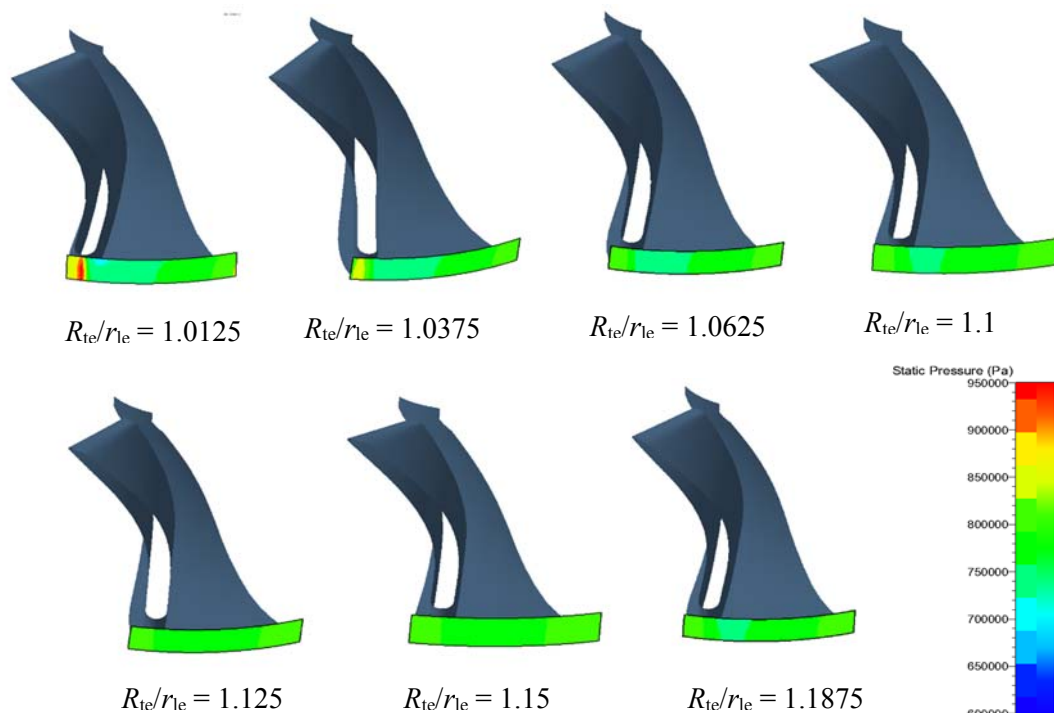
Figure 6. Static pressure distribution in the rotor inlet with varying R_{te}/r_{le}

4. Conclusion

A series of nozzle vanes were successfully designed using commercial blade modeling and numerical analysis tools to investigate the effects that the value of vaneless space, i.e. the R_{te}/r_{le} parameter has on the helium turboexpander stage efficiency. Through matching the mass flow capacity, the meaningful

direct comparisons of varying vaneless space could be carried out. Based on the numerical results, the optimum performance occurred in the design that the value of vaneless space parameter R_{te}/r_{le} was 1.125. The reference design with very small radial clearance ($R_{te}/r_{le} = 1.0125$) led to an obvious reduction in efficiency from the optimum design. When the R_{te}/r_{le} value was in the range 1.1~1.1875, no significant variations in static pressure distribution and efficiency were found. These results indicate that the friction loss due to larger radial clearance is much smaller than the non-uniformity loss due to insufficient turbulent mixing for the helium turboexpander. So increasing the vaneless space was found to be an efficient method of achieving a more circumferentially uniform flow state in the rotor inlet. And a wide range of R_{te}/r_{le} value which achieves high efficiency is convenient for the assembly of helium turboexpanders.

Nomenclature
C_m' = the meridional component of absolute velocity at the rotor inlet
C_2' = absolute velocity at the rotor inlet
C_{2U}' = the circumferential component of absolute velocity at the rotor inlet
n = rotating speed
P_{01} = total pressure at stage inlet
P_3 = static pressure at the stage outlet
q_m = mass flow rate
R_{te} = nozzle vane trailing edge radius
r_{le} = rotor leading edge radius
T_{01} = total temperature at stage inlet
W_2' = relative velocity at the rotor inlet
y^+ = nondimensional distance to the wall
α_2 = flow angle at the nozzle exit
α_2' = flow angle at the rotor inlet
α_{b2} = blade angle at nozzle vane exit
β_2' = relative flow angle at the rotor inlet
η_{t-s} = total to static efficiency
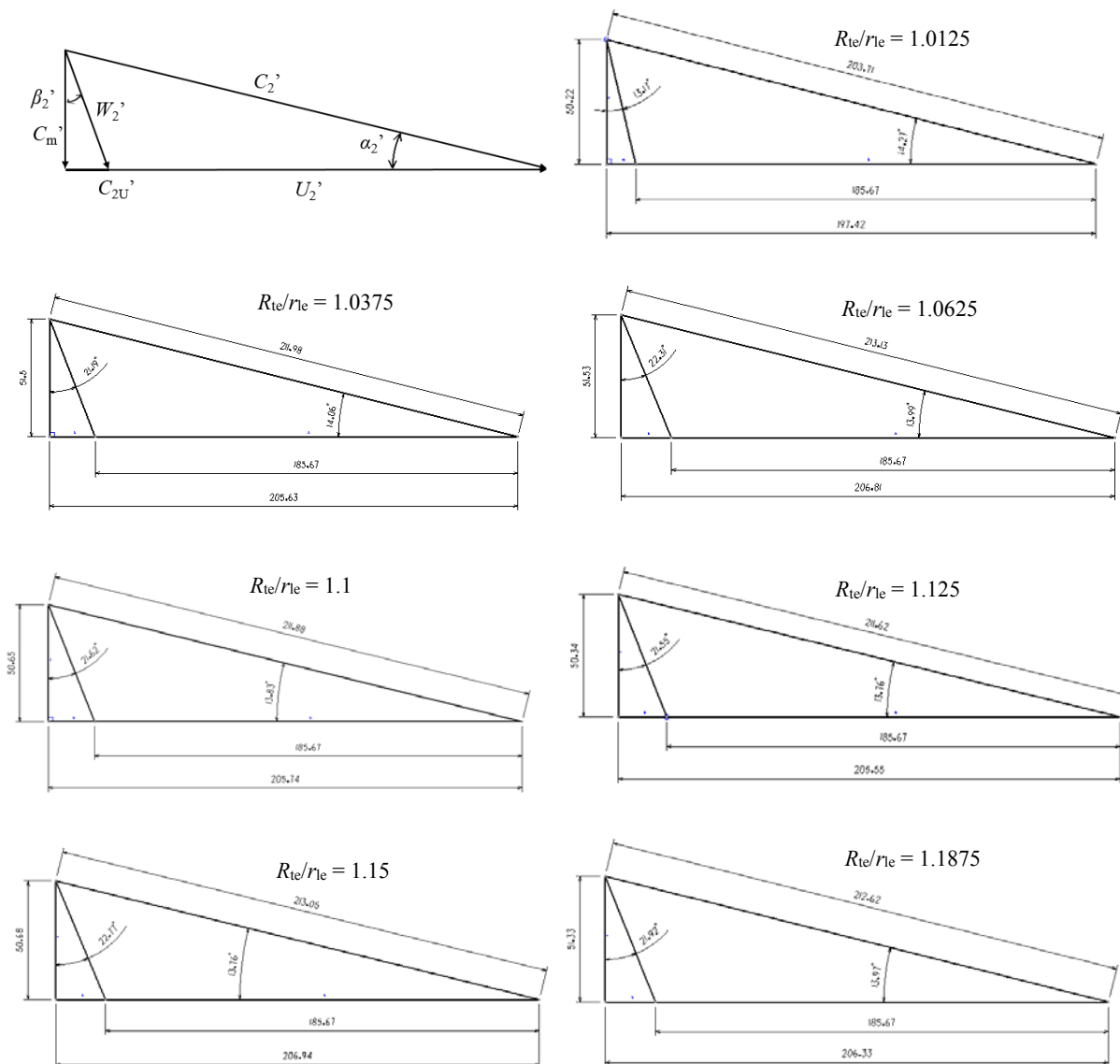σ = stator throat area

Abbreviations
PCD = pitch circle diameter
mfr = mass flow rate

Appendix
The velocity triangles at the rotor inlet with seven designs

References

[1]   Tunakov, A. P. 1960 "Izvestiya vysshikh uchebnykh," (in Russian, "Effect of Radial Clearance
      on the Operation of a Centripetal Gas Turbine") *Zavedeniy Aviatsionnaya Technika*. **4** pp. 83–92.

[2]   Watanabe I, Ariga I, Mashimo T 1971 Effect of Dimensional Parameters of Impellers on
      Performance Characteristics of a Radial-Inflow Turbine *Journal of Engineering for Gas Turbines
      & Power* **93**(1):58

[3]   Simpson A, Spence S, Watterson J 2013 Numerical and Experimental Study of the Performance
      Effects of Varying Vaneless Space and Vane Solidity in Radial Inflow Turbine Stators J*ournal of
      Turbomachinery* **135** 031001-1-12

[4]   Li Yansheng and Lu Guilin 1987 *Radial turbine and centrifugal compressor* (Beijing: China
      Machine Press) p 121