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# Simulation and Design Tool for ORC Axial Turbine Stage

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**Abstract**

Axial flow turbines are the most common expanders for energy conversion. Usually axial flow turbines working fluids are air or steam; nonetheless, there is an increasing interest in evaluating this technology for Organic Rankine Cycle applications. In this field, because of the numerous possible applications, as well as the variety of specific working fluids, the selection of the turbine is usually perfected after a throughout preliminary design of the expander.

Therefore, the main goal of this research is to develop a preliminary design tool for the estimation of power and efficiency of an axial turbine stage working with organic fluids. The implemented thermodynamic model applies systematically real fluid properties. Furthermore, not only a mean line analysis is available in this simulation tool, but also a Non-Isentropic Simple Radial Equilibrium (NISRE) model, in order to evaluate the thermodynamics and kinematics of the flow throughout the blade, is presented.

A geometric parameterization was added to develop an optimal configuration of the channel, which can be adapted to the user requirements, to ensure maximum flexibility for different ORC applications.

The methods applied, as well as various simulation results with different working fluids, from refrigerant to hydrocarbons, are presented.


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*Keywords:* Axial Turbine Stage; ORC; Simulation Tool; NISRE

## 1. Introduction

The relentless increase of energy demand, coupled with the intensification of more stringent environmental standards has brought to the development of technologies for distributed heat and power generation, which can work with low temperature resources. Organic Rankine Cycle (ORC) research, development and commercialization have been therefore expanding at a very high rate in the last years.

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**Nomenclature**

| | |
|---|---|
| 0,1,2 | Referred to section 0,1,2 (fig. 1b) |
| $\alpha$ | Absolute flow angle [°] |
| $\beta$ | Relative flow angle [°] |
| A | Power law coefficient |
| b | Axial chord [m] |
| B | Power law coefficient |
| c | Absolute velocity [m/s] |
| H | Blade height [m] |
| h | Enthalpy [J/kg] |
| ISRE | Isentropic Simple Radial Equilibrium |
| n | Power law exponent |
| NISRE | Non-Isentropic Simple Radial Equilibrium |
| $n_s$ | Specific Speed [-] |
| o | Throat section [m] |
| ORC | Organic Rankine Cycle |
| r | Radius [m] |
| RPM | Revolution per minute |
| s | Entropy [J/kgK] |
| T | Temperature [K] |
| U | Peripheral velocity [m/s] |
| $\dot{V}$ | Volume Flow rate [$m^3$/s] |
| w | Relative velocity [m/s] |

In order to have the most accurate prediction of the effective ORC power and efficiency potentials, the design of the expander is fundamental. As the ORC power and hot temperature resources vary strongly depending on the application, the expanders' variety is as wide. Turbines as well as volumetric expanders (scroll, screw or piston) are employed depending on hot source and power range. Axial turbines are widespread used for power, which range between 500 kW and various MW power, radial turbines seem more fitted for lower power ranges (50-500 kW) and volumetric expander are usually utilized for small to micro power generation.

Recently, useful guidelines on the design and performance estimation of volumetric expanders [7, 12, 18] as well as on radial inflow turbines [5, 6], for ORC have been developed.

On the other hand, the design of an axial turbine for ORC has been investigated since 1977 [13, 15]. From those milestones, numerous other researches have been carried out, which include the prediction of efficiency of axial turbine stage with ORC fluids [14], the development of a mean line tool for preliminary design for the optimization of the turbine stage [11], and the assessment of new efficiency charts for ORC axial turbines [2, 3].

The principal aim of this study is to develop a design and performance prediction tool for ORC axial turbine stage, applying the well-established knowledge on mean line analysis tools [2, 3, 14, 15] and extending this tool capability in order to investigate the behavior of the fluid throughout the height of the blade. *The objective is therefore to apply the radial equilibrium theory in order to develop an ISRE (Isentropic Simple Radial Equilibrium) and NISRE (Non Isentropic Simple Radial Equilibrium) simulation tool for ORC axial turbine stage.*

The final purpose of this study will be to provide a free-source tool for academic applications, which include mean line and NISRE approach analysis that could be used for preliminary design of ORC axial turbine stage.

## 2. Methodology

In order to develop a preliminary design tool for the estimation of power and efficiency of an axial turbine stage working with organic fluids, the classical thermodynamic axial stage design was applied [1, 4, 8]. Particularly, first a mean line approach is implemented, and after that specific subroutines extend the analysis throughout the blade height applying ISRE and NISRE models.

### *2.1. Mean Line Analysis*

The design code firstly assesses the thermodynamics, as well as the kinematics, of the flow at the mean diameter for each blade row. In order to estimate the thermodynamic of the flow, the model evaluates the working fluid as real fluid (that is, neither incompressible nor ideal gas). All thermodynamic properties are evaluated depending on the local variables (typically, p and T) with real fluid assumption, at present using the Engineering Equation Solver library data [9]. The code requires some inputs, which are chosen following both the classical design approach [8] and previous examples on mean line analysis of ORC axial turbine [2, 3, 14, 15]. The input parameters of the code are resumed in table 1.

Table 1. Input parameter for Mean Line analysis. Section 0 corresponds to Stator Inlet, 1 to Stator Outlet, 2 Rotor Outlet

| Parameter | Symbol | Unit |
|---|---|---|
| Stage Inlet Total Pressure | $P_{00}$ | [Pa] |
| Stage Inlet Total Temperature | $T_{00}$ | [K] |
| Stage Outlet Total Pressure | $P_{02}$ | [Pa] |
| Flow Coefficient | $\phi = c_{x0}/U_0$ | [-] |
| Load Coefficient | $\psi = \Delta h0_{is}/U_0^2$ | [-] |
| Degree of Reaction | $R = (h_1 - h_2)/(h_0 - h_2)$ | [-] |
| Total to Total Efficiency | $\eta = (h_{00} - h_{02})/(h_{00} - h_{02ss})$ | [-] |
| Stator Aspect Ratio | $AxCRS = H_1/b_1$ | [-] |
| Rotor Aspect Ratio | $AxCRR = H_2/b_2$ | [-] |
| Specific Diameter | $D_s$ | [m] |
| Diameter Taper | $TaperD = D_2/D_0$ | [-] |
| Axial Velocity Taper | $AmplCX = c_2/c_1 = c_1/c_0$ | [-] |
| Fluid | - | [-] |

A relevant feature of the code is its feasibility to simulate diameter changes at each section applying different TaperD values and to control the axial velocity throughout the stage by the axial velocity taper.

Starting from the assigned inputs, the code starts real fluid calculation of thermodynamic and kinematics parameters of the points 0, 1 and 2.

The first step is the definition of the stage inlet and exit total points, which are calculated through the assumption of a first guess total-to-total efficiency. Assuming repeating stage design, static points 0 and 2 can be determined, as well as the corresponding absolute and relative velocities. The blade heights at station 0 and 2 are determined through the application of continuity equation.

An optimization algorithm (the “Golden section search” or “the Quadratic approximations”), which takes as optimizing variable the entropy at point 1, is utilized to define point 1 and 01. The utilization of the optimization algorithm is due to the application of Aungier’s loss model [1], which is the most recent update of the Ainley-Mathieson loss model. The most recent loss correlations have been preferred to a classical approach, because, classical loss models, for small-scale ORC turbines could give a 15% difference in efficiency prediction [10].

Therefore, an iterative procedure allows the calculation of the stator loss coefficient. Finally, the optimized stator design provides the starting point for rotor design parameters calculation. If a not feasible geometry is found, a new total-to-total efficiency value is guessed until a proper configuration is obtained. The optimum space to chord ratio of the cascade is computed through the application of Zweifel’s criterion [8]. The main geometric parameter restrictions are displayed in table 2.

Table 2. Upper and lower bounds for geometric optimization, as suggested in [2].

| Parameter | Lower limit | Upper limit |
|---|---|---|
| AxCRS | 0 | $2/3 + H_0/b_1$ |
| AxCRR | 0 | $2/3 + H_1/b_2$ |
| $(o/s)_S$ | 0.225 | 0.866 |
| $(o/s)_R$ | 0.225 | 0.866 |

The code finally calculates the total to static efficiency of the stage and verifies the soundness of the results computing the specific work in three different forms.

Another possible approach of optimization, which the code allows, is the global optimization of the total to static efficiency. EES software has already implemented 5 multi variable optimization algorithms ("Conjugate Directions method", "Variable Metric method", "Nelder-Mead Simplex method", "DIRECT Algorithm", "Genetic method") [9]. Therefore, if the optimum total to static efficiency is investigated (not the optimal stator design), a multi-variable algorithm can be utilized, employing as optimizing variables total-to-total efficiency and entropy at point 1.

Figure 1a displays the model's flowchart and figure 1b depicts the thermodynamic point in the enthalpy-entropy diagram.

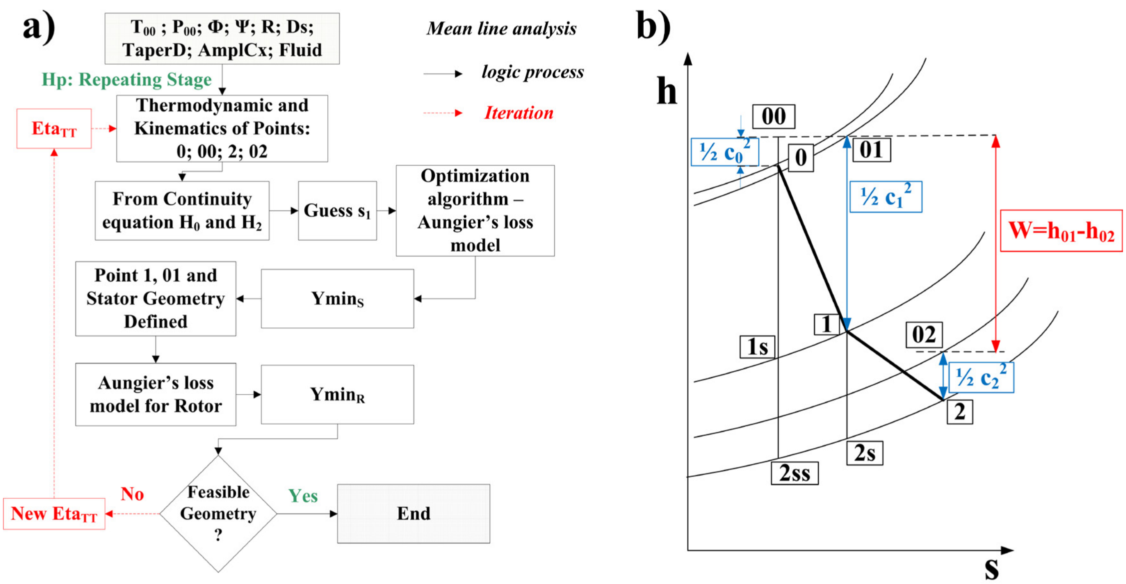


Fig. 1 a) Model's flowchart: black line indicates logic process, red dashed lines indicates iteration process. b) Enthalpy – Entropy diagram of axial turbine stage with reference notation.

### 2.2. ISRE

The extension from mean line model to 2D or 3D models is derived from Wu theory [17], following the traditional decomposition of turbomachinery flows in Mean Line and Blade to Blade.

The radial equilibrium analysis is built on the assumption that the value of radial velocities is constant. The other important assumption is that the flow is axisymmetric. Therefore, from the analysis of the radial equilibrium of a fluid element, equation (1) can be derived [8].

$$\frac{\mathrm{dh}_0}{dr} - \frac{Tds}{dr} = c_x\frac{dc_x}{dr} + \frac{c_\theta}{r}\frac{d}{dr}(rc_\theta) \quad (1)$$

The Isentropic Simple Radial Equilibrium theory assumes that $ds/dr = 0$, therefore equation 1 can be simplified to equation 2.

$$\frac{\mathrm{dh}_0}{dr} = c_x\frac{dc_x}{dr} + \frac{c_\theta}{r}\frac{d}{dr}(rc_\theta) \quad (2)$$

Another important assumption, which is often made during a turbomachine design, is to consider it as adiabatic and reversible and to keep the work at each rotor radius constant. These assumption imply $dh_0/dr = 0$, allowing a further simplification of equation (2) to (3).

$$c_x\frac{dc_x}{dr} + \frac{c_\theta}{r}\frac{d}{dr}(rc_\theta) = 0 \quad (3)$$

The final step of ISRE analysis is to determine a design law for tangential velocities. A general whirl distribution [11] was implemented, with a general distribution equation given by equation (4):

$$c_\theta = Ar^n \pm \frac{B}{r} \quad (4)$$

The plus sign is applied downstream the rotor flow and the minus sign is applied upstream the rotor flow. The implemented distributions comprehend the free vortex design (n=-1), the constant degree of reaction design (n=1) and the exponential design (n=0).

### 2.3. NISRE

The Non Isentropic Simple Radial Equilibrium (NISRE) was already set in equation (1). In order to implement this law, it is first necessary to resolve the ISRE calculations.

Once the ISRE computations are accomplished, guess values for the mass flow rate in each flow stream, as well as the static pressure at each blade height are available.

One basic assumption to resolve equation (1) is therefore to impose the same static pressure and mass flow rate calculated in the ISRE model in each flow stream, assuming that the flow streams do not mix. Furthermore, for the stator blades it is also imposed that total enthalpy is conserved for each flow stream; the same holds for rothalpy for rotor blades.

An iterative procedure on local blade angles is implemented for stator and rotor sections in order to calculate the effective local losses, which are again computed through Aungier's loss model.

## 3. Code Validation

In order to develop a sound analytical tool for axial stage turbine design, the validation on the computed results is required. Therefore, one of the reference axial stage configuration simulated in [2] has been replicated with the developed in-house code and the comparison of the obtained results has been resumed in table 3. The results achieved closely match the ones present in literature. Furthermore, the ISRE blade angle distribution through the stage has been compared with the one presented in [16] (fig. 2).

Table 3. Comparison of simulated results from the developed code and the results estimated in [2], for r245fa

| Parameter | Present work | | [2] | |
|---|---|---|---|---|
| Flow Coefficient ϕ | 0.4 | | 0.4 | |
| Load Coefficient ψ | 1.05 | | 1.05 | |
| Degree of Reaction R | 0.45 | | 0.45 | |
| Size Parameter SP | 0.22 | | 0.16 | |
| Volume Ratio VR | 1.7 | | 1.7 | |
| Total to static efficiency | 0.89 | | 0.891 | |
| Axial velocity [m/s] | 38 | | 37.5 | |
| | Stator | Rotor | Stator | Rotor |
| Mach Inlet | 0.29 | 0.28 | 0.28 | 0.28 |
| Mach Outlet | 0.77 | 0.7 | 0.79 | 0.73 |
| Profile Loss | 0.019 | 0.019 | 0.015 | 0.016 |
| Secondary Loss | 0.026 | 0.052 | 0.034 | 0.027 |
| Trailing Edge Loss | 0.006 | 0.012 | 0.006 | 0.011 |
| Shock and Diffusion Loss | 0.009 | 0.01 | 0 | 0 |
| Post-expansion Loss | 0 | 0 | 0 | 0 |
| Clearance Loss | - | 0.093 | - | 0.071 |
| Loss Coefficient | 0.060 | 0.186 | 0.056 | 0.124 |

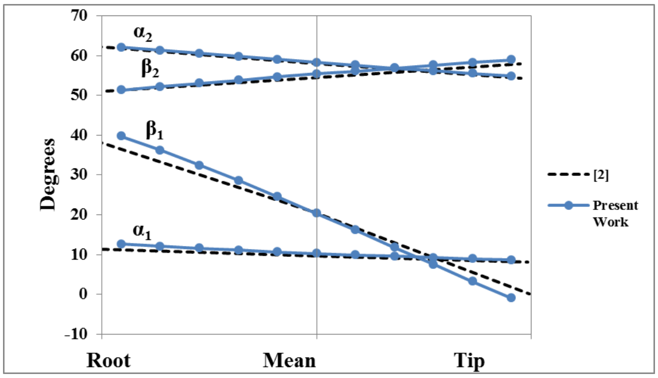


Fig. 2 Comparison of simulated ISRE angle distribution against [2]; Fluid = Air; $T_{00} = 1100$ [K], $P_{00} = 0.4$ [MPa]

## 4. Results

This section shows some results obtained through the computations. Two working fluids were selected to demonstrate the versatility of the code. In particular, the simulated working fluids are, R245fa, as one of the most common fluid for ORC, and n-Hexane, as an example of hydrocarbon calculation.

The main parameter cross-checked for all mean simulations is the total to static efficiency at different flow and load coefficient and for different size parameters and volume ratios.

For the Blade-to-Blade design, the NISRE flow angles variations at each blade height are shown (fig. 5a, 5b). The displayed results were obtained for a free vortex design configuration (n=-1).

Total temperature and pressure were fixed as suggested by reference [6]. The total conditions for each fluid are resumed in table 4.

Table 4. Total Inlet Input parameter for calculations

| Fluid | $P_{00}$ [MPa] | $T_{00}$ [K] |
|---|---|---|
| R245fa | 3.1 | 420 |
| N-hexane | 0.6 | 420 |

The efficiency maps generated for each fluid show a common trend, both for the Φ - Ψ maps and for the VR-SP maps. As it was expected, higher efficiencies are reached for low values of Φ and values of Ψ in the range of 1-1.3. Another awaited outcome is the trend of efficiency when varying VR and SP. Indeed, as it was demonstrated in reference [3], optimal efficiency values are reached for high values of SP and low values of VR.

High values of VR determine Mach numbers in the supersonic region. Figure 3b and 4b display the maximum VR before the relative velocity at rotor outlet and the absolute velocity at stator outlet become sonic.

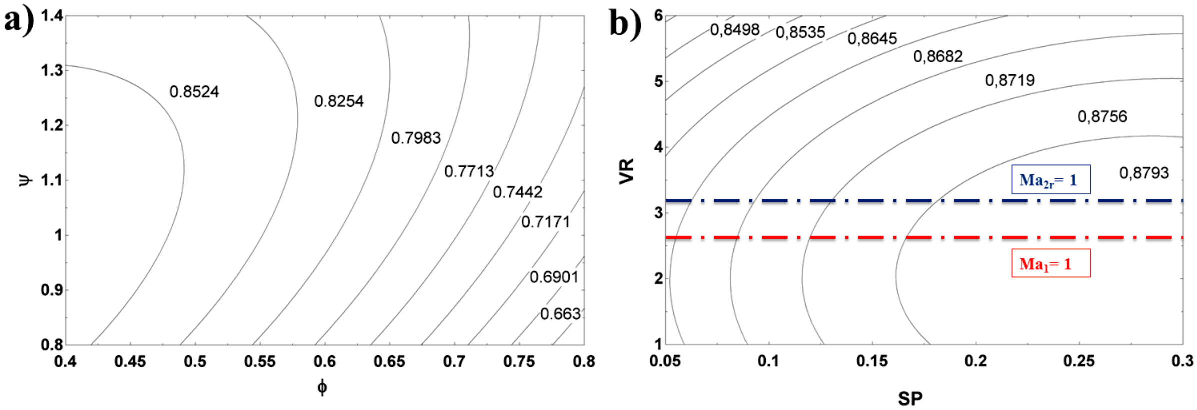


Fig. 3 R245fa, a) ϕ – ψ diagram. b) SP-VR diagram

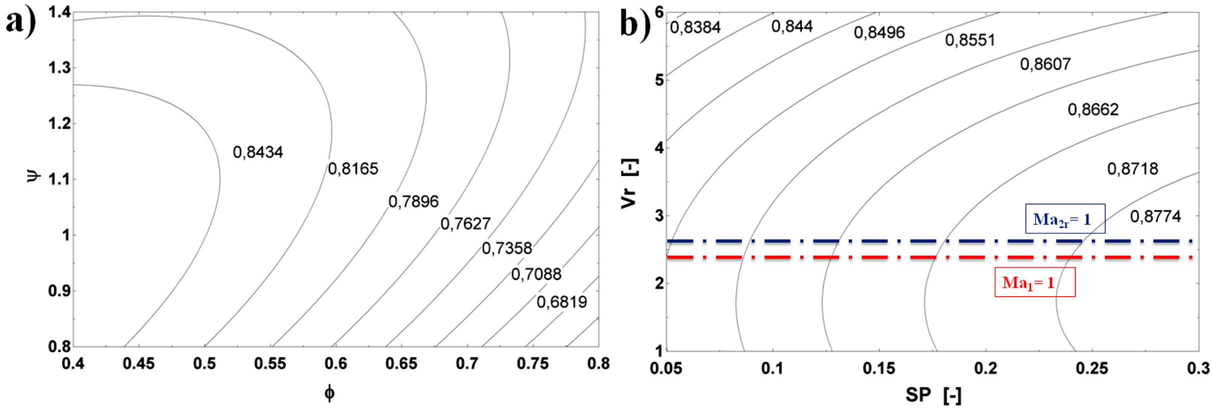


Fig. 4N-hexane; a) ϕ – ψ diagram. b) SP-VR diagram

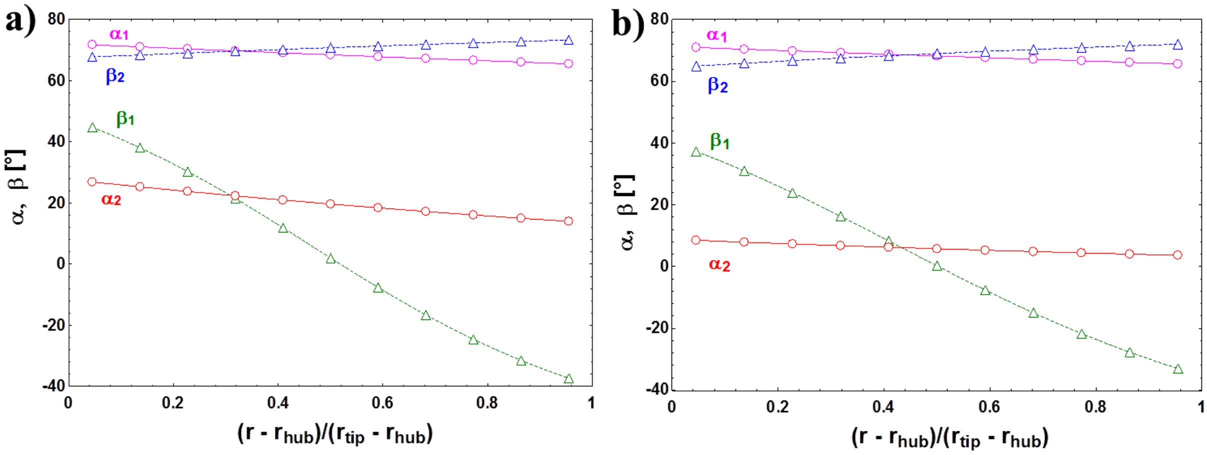


Fig. 5 Free Vortex Design; NISRE angle distribution for a) R245fa; b) N-hexane

Different fluids slightly affect the angle distribution both at stator and rotor outlet (fig. 5). Indeed, the angle distribution is mainly dependent on the power law selected and on the selected non-dimensional parameters.

The efficiency calculation through the application of NISRE approach matches the efficiency prediction of the mean line analysis. Nonetheless, from the angle distribution behavior throughout the blade it is possible to recognize instantly where the inefficiencies occur.

## 5. Conclusions

A simulation and design tool for axial turbine stage was developed in this project and was utilised for evaluating the efficiency using two different organic working fluids. The results obtained demonstrate the feasibility of a novel approach avoiding any reference to ideal gases or approximate Equations of State, as are commonly used in many turbomachinery applications (including modern CFD tools). This approach represents an important novelty for ORCs, which often operate in the near-critical region. The key results from the study may be summarized as follows:

- A mean line analysis of an axial turbine stage for ORC was developed. The goal was to estimate the correct geometric parameters of the blades, such as the proper mean diameter and blade height, and to get a clear understanding of the machine at mean line diameter for several working fluids. The implementation of two taper, one on axial velocity and one on inlet/outlet stage mean diameter ratio, allowed the realization of a simple flexible design tool.

- ISRE and NISRE approaches for the design of the blade were applied to organic fluids, allowing "quasi-3D" design of the blades, from hub to tip, and the comprehension of the thermodynamics, as well as the kinematics characteristics of the fluid at each blade height. This procedure also allowed to define the local velocities triangles, as well as the degree of reaction at each radius.
- Several fluids were simulated, obtaining sound results and demonstrating the adaptability of the code when the fluid is changed.

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