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# *Modelling Analysis of a Saturated Steam Turbine with Respect to Multi-body Dynamics*

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***Abstract:*** In petroleum, chemical, light industry, metallurgy, building materials, paper making, textile and other industrial enterprises there is a large amount of low-grade energy a low-pressure saturated steam, these low-grade energy except for a small amount of recycling, a large number of emptying, resulting in a great waste of energy. The aim of this paper is to investigate the modelling analysis of saturated steam turbines with respect to multi-body dynamics. The paper systematically analyses methods and key technologies for the recovery and utilisation of low-value thermal energy, as well as the design, development and optimisation of specific industrial low-pressure saturated steam turbines to improve the performance of waste heat recovery systems. Energy conservation and reduction of consumption are of great importance to industrial companies. to reduce the risk of steam-induced blade corrosion. A small 100 kW waste heat recovery turbine was designed for liquid saturated steam at a flow rate of 1 tonne per hour and a pressure of 0.8 MPa. The unit is characterised by its high efficiency and small structural dimensions. This feature is intended to solve the problem of low efficiency and difficulties in recovering waste heat due to the uneven distribution of the heat source and its small size. The application site can be a small factory or a house. This paper focuses on the structural design and calibration of key turbine components, such as moving blades, impellers and cylinders. The maximum error of the hybrid model in this paper is experimentally proven to be within 3%, indicating that the hybrid model of the turbine body is consistent with the actual operating conditions and meets the engineering accuracy requirements.

## 1. Introduction

Industrial companies, chemical plants with nitric acid plants, methanol synthesis plants with waste heat boilers, petrochemical companies, e.g. polyester oxidation plants with steam generators. The low temperature and humidity of the steam, the low resistance to flow over long distances and the high humidity in the pipes and equipment cause severe corrosion and make the efficient use of energy more difficult [1-2].

In the research on the modelling and analysis of saturated steam turbines with multi-body dynamics, many scholars have studied it with good results, e.g. Bermudez G F, in his analysis of the relationship between steam parameters and flow rate before and after changing the operating conditions of the trapezoidal group, based on operating experience and experimental results, a three-dimensional plot between steam flow rate and starting pressure and back pressure in the trapezoidal group can be obtained, which is Sttla flow cone [3]. Yamashita H proposed the optimised IAPWS-IF97 formulation. Due to the simplicity of the model, the accuracy of the results and the wide range of thermal parameters, the formula quickly spread internationally upon publication and is now a standard formula for industrial calculations [4].

This paper focuses on the modelling of a large condensing turbine system and the optimisation of the initial pressure of operation, with a focus on the characteristics of the turbine system itself and its subsystems. The paper uses the commercial software CFX to carry out numerical simulations and analyses of the shaft seal, bulkhead seal and perimeter belt seal to identify the main sources of turbine airflow excitation occurrence, and to carry out analytical studies on the improvement of these three seal structures to improve their stability based on the studies of the Childs experimental structure and the Pugachev experimental structure.

## 2. A Study on the Modelling and Analysis of Saturated Steam Turbines with Multi-Body Dynamics

### 2.1. Final Steam Parameters

(1) For condensing turbines, the discharge pressure has a certain relationship with the cooling water temperature, as shown below.

$$t_s = t_{w1} + \Delta t + \delta t \tag{1}$$

Where

$t_s$ -Saturation temperature of spent steam, ℃;

$t_{w1}$ -Inlet temperature of cooling water, ℃.

$\Delta t$ -Temperature rise of the cooling water in the condenser, ℃;

$\delta t$ -Difference in the heat transfer end of the condenser, ℃.

(2) For back-pressure turbines, the discharge pressure is designed according to the needs of the actual situation, with reference to the commonly used discharge pressure values for back-pressure turbines in China [5-6].

### 2.2. Detailed Calculation of Turbine Parameters at All Levels

Before the calculation of parameters at all levels, the inlet steam flow of the turbine has to be estimated, which is calculated as follows [7-8].

$$G = \frac{N}{\Delta H_a (1 - j)\eta_{ri}} \tag{2}$$

Where

N - turbine design power, kW.

$\Delta H_a$ - ideal enthalpy drop of the turbine, J/kg.
j - total turbine flow leakage factor, often taken as 0.03.
$\eta_{ri}$ - Calculated internal efficiency of the turbine, taken as 0.75.

Afterwards, detailed calculations of the various parameters of the stage are carried out. The process consists of determining the working pressure before and after the stage, determining the ideal enthalpy of the stage, determining the steam thermal parameters of the stage, determining the structural design parameters of the stage, determining the various losses of the stage, determining the efficiency of the stage, the power of the stage and other parameters. A detailed flow chart is shown in Figure 1 below.

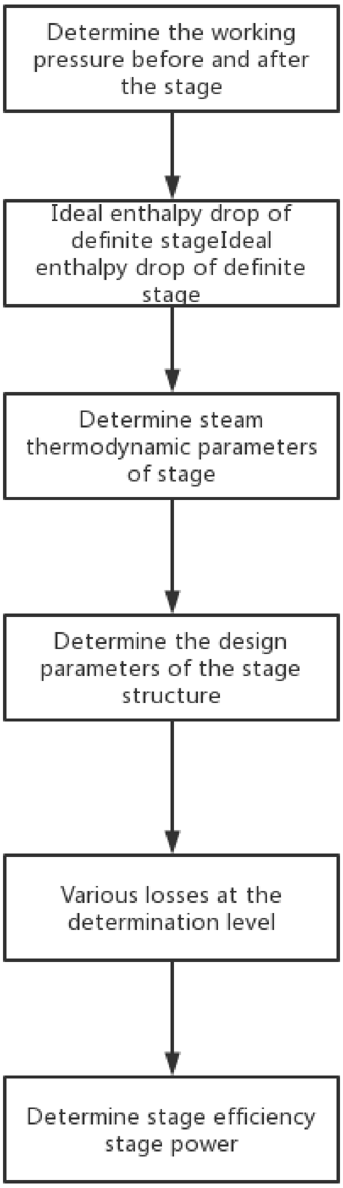


*Figure 1. Steam flow parameters calculation process*

### 2.3. Writing of the Main Program

The main program of this paper mainly includes parameter input module, parameter call module, stage number calculation module, estimation of turbine flow module, stage thermal and structural parameters calculation module, calculation of each loss of stage module, actual power calculation module, loop iteration module and parameter output module, etc., which are described in detail below [9-10].

(1) Parameter input module

The main function of the parameter input module is to input and extract known parameters. The known parameters in this program include turbine inlet and outlet pressures, external dehumidification device pressure loss coefficients and stage coefficients etc. These parameters are written in the text box component and the conversion function in the program is used to convert the text information in the text box into double precision real variables for the calculation of the parameters in the program.

(2) Parameter call module

The parameter call module focuses on calling variables within windows and between windows in the program.

(3) Estimation of turbine flow module

The ideal enthalpy drop of the turbine, the flow leakage coefficient of the turbine and the calculated internal efficiency of the turbine are used to determine the inlet steam flow.

(4) Actual power calculation module

The actual power calculation module calculates the actual power of the turbine. The actual power of each stage is determined by calculating the losses in the regulated, unregulated and low pressure stages of the high pressure cylinder, and the total actual power is obtained by summing up the total [11-12].

(5) Parameter output module

The main function of the parameter input module is to output the parameters of the calculation results. The calculated parameters in this program include turbine inlet and outlet pressures at all levels, dryness, flow rate, efficiency, power, nozzle dynamic lobe height, etc. The conversion function in the program is used to reconvert the double precision real variables to text information in a text box, which is written in the text box component for output [13-14].

### 2.4. Turbine System Characteristics Model

The establishment of a model of the characteristics of each equipment of the turbine system is an important basis for the analysis of the variable operating conditions and operation optimization of the system. In this section, the mechanism models of the turbine body, the cold end system, the heat return system and the feedwater system are established respectively for the characteristics of the object of study in this paper.

(1) Turbine body characteristics model

The turbine body consists of a regulating stage and several pressure stages. When the unit is operating under variable load, the through-flow area of the regulating stage distribution mechanism will vary with the opening of the regulating valve, while the through-flow area of the pressure stage is fixed. Therefore, in this paper, the flow characteristics of the regulating valve are first analyzed and the thermal calculation analysis of the regulating stage is carried out [15-16], and then the other stage groups are divided according to the vapour extraction ports, with one stage between every two extraction ports, in order to realize the variable working condition calculation of the whole machine.

(2) Analysis of flow characteristics of regulating valves

The flow characteristics of the valve is to determine the flow rate through the valve at a given opening according to known conditions, or to determine the opening of each valve at a known valve flow rate, usually expressed in terms of the characteristic curve of the valve. When the unit is operated under pressure in the sequential valve mode, the main steam pressure, the valve opening and the unit load are in a mutually constraining relationship. Under different loads, there is a combination of valve openings corresponding to the optimal initial operating pressure of the unit, i.e. the optimization of the initial operating pressure of the unit is closely related to valve management, and mastering the valve flow characteristics is an important prerequisite for completing the flow distribution of the unit, achieving accurate control of the unit and ensuring optimal operation of the unit [17-18].

## 3. Research Design Experiments on the Modelling and Analysis of Saturated Steam Turbines with Multi-Body Dynamics

### 3.1. Data Pre-Processing

Data pre-processing is an important step before data-driven modelling by screening the raw measurement data of the process to improve data reliability and credibility.

(1) Data Cleaning

Data cleansing is the process of detecting and processing incomplete, redundant and abnormal data in the target data according to the operational characteristics of the equipment and existing theoretical methods, so as to obtain clean data that meets data quality standards and application requirements.

Step 1, raw data analysis. The purpose of the analysis of the raw data is to identify possible problems in the data, which is the basis of data cleaning; Step 2, determine the cleaning rules. According to the problems in the data to determine the corresponding cleaning rules, and select the appropriate cleaning method; step 3, rule verification. In order to ensure the rationality of the cleaning rules and cleaning methods, you need to collect some sample data to verify them, if the cleaning effect is good, then carry out all data cleaning, if the cleaning effect does not meet the requirements, then redefine the rules and methods until they meet the requirements; step 4, data cleaning. According to the reasonable cleaning rules and methods to clean the data, to get clean data that meet the requirements of modelling.

(2) Steady state detection

The model built in this paper is a static characteristic model of the turbine system, which only considers the characteristic relationship under the steady state of the unit, while thermal power units are often in variable operating conditions, and during the variable operating conditions, due to the differences in mass inertia and thermal inertia between different equipment, the parameter changes are not synchronized, which cannot correctly reflect the static characteristics of the equipment. Therefore, steady-state testing of the data is required prior to modelling. In this paper, an adaptive noise removal algorithm based on a Gaussian filter is used to de-noise the data, and then an R-test is used for steady-state detection.

### 3.2. Experimental Design

This paper presents an analysis of the turbine model constructed in this paper. Firstly, the error of the turbine body model constructed in this paper is investigated, and the relative error of the regulating lonely model and the pressure machine model are investigated separately. Secondly, the variation of the turbine under variable operating conditions is investigated.

## 4. Experimental Analysis of a Study on the Modelling Analysis of a Saturated Steam Turbine with Multi-Body Dynamics

### 4.1. Turbine Body Model

In this paper, the error statistics of the turbine ontology model constructed in this paper are studied, and the relative errors of both the regulation level model and the pressure level model are studied for the mechanistic and hybrid models, and their error data are recorded, and the data are shown in Table 1.

*Table 1. Steam turbine ontology model error statistics*

| | Regulatory-level model A mechanistic model | Regulatory Level Model Hybrid Model | Pressure-level model A mechanistic model | Pressure-level Model Hybrid model |
|---|---|---|---|---|
| Crest value% | 7.145 | 2.885 | 10.891 | 2.511 |
| Least value% | 0.024 | 0.012 | 0.022 | 0.016 |
| Average value% | 5.009 | 1.567 | 6.781 | 1.056 |

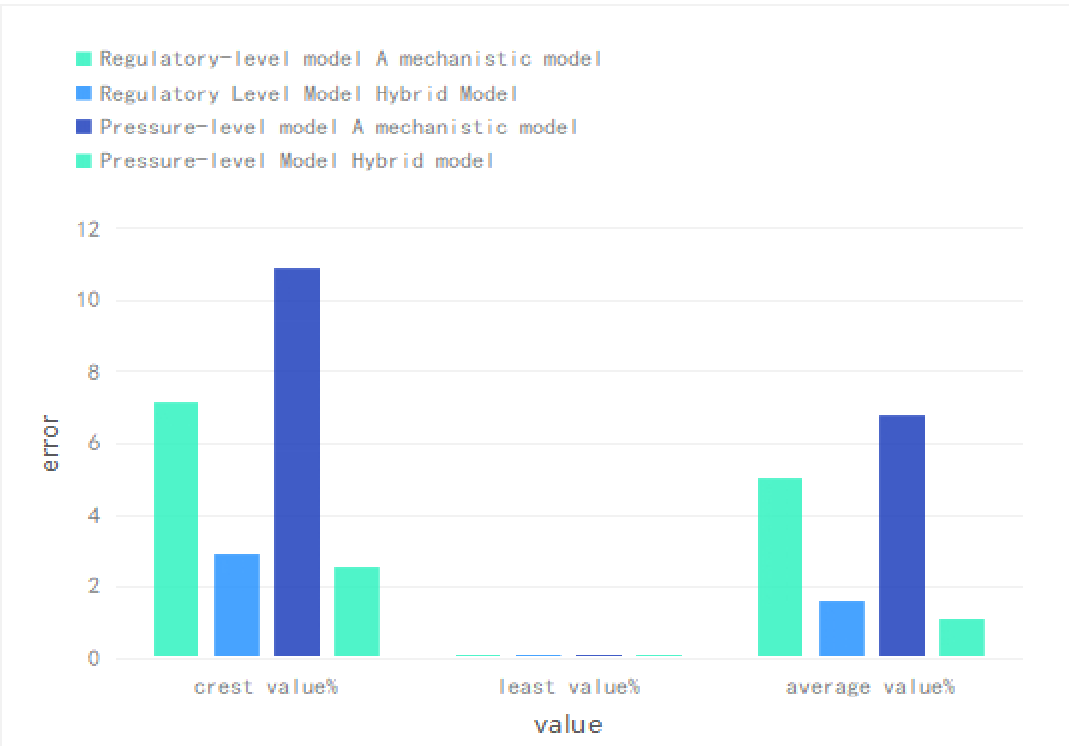


*Figure 2. Comparison of relative errors between adjustment level and pressure level models*

Since the last pressure stage is wet steam, the discharge pressure and temperature can only be monitored on site, so the enthalpy of discharge and the efficiency of the last stage cannot be calculated, so this correction method is not applicable to the eight pumping to the discharge port pressure stage group. However, as the turbine body is divided into stage groups by the extraction port, the post-stage parameters of the upper stage group are the pre-stage parameters of the lower stage group, and when the other pressure stage groups are corrected, the final pressure stage group and the regulating stage will also be corrected. The error statistics of the turbine body model are shown in Figure 2. The maximum error of the hybrid model is within 3%, indicating that the hybrid model of the turbine body is consistent with the actual operating condition and meets the engineering accuracy requirements.

## 4.2. Thermal Analysis of Variable Working Conditions

The results of the calculations are shown in Table 2 below, after entering the variation parameters into the saturated steam turbine variation thermal analysis program.

*Table 2. Calculate the resulting parameters*

| Parameter | Program values | Actual value |
|---|---|---|
| Unit efficiency | 0.563 | 0.543 |
| Power of the assembling unit (MW) | 4.155MW | 4.25MW |

As can be seen from the above table, the difference between the calculated efficiency and power of the unit and the actual value is 3.3% and 2.2% respectively, which is within the design tolerance range and the calculation results of the variable working conditions are reliable. At this time, the program calculates the reaction degree of all levels as shown in Table 3 below.

*Table 3. Reaction degree parameters of all levels*

| Degree of reaction | High pressure cylinder adjustment grade | High-pressure cylinder is non-regulating stage | Pressure level of low pressure cylinder |
|---|---|---|---|
| Design working condition value | 0.1 | 0.1 | 0.1 |
| Varying duty | 0.042 | 0.071 | 0.064 |

After the change of working conditions, the reactivity of the high-pressure cylinder regulating stage, the non-regulating stage and the low-pressure cylinder pressure stage all decrease, because the turbine speed decreases and the reactivity decreases according to the formula for calculating the reactivity; while the high-pressure cylinder regulating stage decreases to a greater extent, because the enthalpy drop of the regulating stage increases to a greater extent after the change of working conditions and the reactivity decreases to a greater extent.

## 5. Conclusion

This paper meticulously analyses the detailed process of calculating parameters at each step of the process and provides a theoretical basis for writing a thermal design program. Using the thermal parameters of a turbine as an example, the calculation results of the program are within the design tolerance and the design results are reliable. Based on this, a thermal analysis study of the thermal performance of this turbine under design and variable operating conditions is carried out.

In design metric conditions.

(1) The dryness of the final stage of the low-pressure cylinder rises with the increase of the discharge pressure, and the height of the final stage dynamic vane decreases with the increase of the discharge pressure, and both the increase and decrease are small.

(2) The dryness of the final stage of the low-pressure cylinder increases with the increase of internal dehumidification efficiency, and the height of the final dynamic lobe decreases with the increase of internal dehumidification efficiency, and both the increase and decrease are larger; the dryness of the final stage of the low-pressure cylinder and the height of the final dynamic lobe increase with the increase of external dehumidification efficiency, but the increase of the final dryness of the low-pressure cylinder is larger.

Under variable working conditions.

The reactivity of the high-pressure, non-regulated and low-pressure cylinder pressure stages of the turbine is reduced compared to that of the corresponding stages under design conditions, and the reduction in the reactivity of the high-pressure cylinder regulation stage is greater.

Throughout the design process, the selection of some parameters is simplified (e.g. the efficiency parameters of the internal and external dehumidification units), which can be studied later in the design process, based on a detailed analysis of the actual situation and the identification of the corresponding parameters to be selected. Then the procedure will also be more complete.

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## Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

## Conflict of Interest

The author states that this article has no conflict of interest.

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