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A New Steam Turbine Model for Utility System Design and Optimization

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Steam turbine shaft power performance and efficiencies depend on turbine size, type, and operating conditions. This work develops a new turbine performance model based on thermodynamic principles and semi-empirical equations to obtain general steam turbine performance estimation. Moreover, the basis of performance model and its relation to turbine efficiencies is analyzed to make clear how key operating and structural parameters affect the performance model. The new model has been validated against commercial steam turbine data and literature data and gives high accuracy for a wide range of steam turbines. The proposed model overcomes problems from previous models, which did not account for changes in steam mains pressures, and can be applied in utility system design, operational optimization, and system retrofit with complex multi-stage turbines allowing for changes in steam header conditions directly.

1. Introduction

Steam turbines perform important roles on cogeneration in utility systems in three ways: steam distribution to balance process steam requirements; shaft power generation in turbine expansion; and driving rotary equipment directly. As the basic component in the system, steam turbine performance needs to be estimated for utility system design and optimization, especially at part-load operation, because utility systems always feature redundancy to allow for changes in operation, breakdown and maintenance.

Some models have been proposed for turbine performance estimation. Raissi (1994) investigated a temperature enthalpy model to represent power estimation graphically, but the same conversion coefficient for every steam expansion zone leaded to errors in the calculation. Harell (2004) provided a concept of extractable power and header efficiency to establish cogeneration potential based on graphical representation. However, these models did not take account of steam superheat temperature.

Other models were principally based on exergy analysis (Marechal and Kalitventzeff, 1997). Sorin and Hammache (2005) presented an exergetic model that power was not linear to steam saturation temperature drop. These models essentially reflected an ideal thermal engine performance.

Bandyopadhyay et al. (2010) developed a linear model based on the Salisbury approximation (1942) and energy balance. Mavromatis and Kokossis (1998) formulated a non-linear model to incorporate efficiency variation with turbine size and operating load. Shang (2000) extended the model to include the influence of turbine size on its performance. Varbanov et al. (2004) established an improved turbine hardware model (THM). These models had limited accuracy due to their inbuilt assumptions that coefficients in the model were determined only by steam saturated temperature drop across a turbine.

Flores and Nunez (2010) correlated steam temperature and enthalpy as a function of the exhaust pressure to form a modified thermodynamic model. The iterative nature of the model limited its straight forward utilization.

Mathematical programming has also been developed for power estimation. Mohan and El-Halwagi (2007) introduced a linear algebraic approach based on extractable power and steam mains efficiency. El-Halwagi et al. (2009) developed a shortcut method within a quick targeting methodology based on both mass and heat integration. Ghannadzadeh et al. (2011) proposed a Bottom-to-Top Model as the shaft

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work targeting model. Kapil et al. (2012) combined bottom up and top-down procedures for power prediction considering steam superheat temperature. Luo et al. (2011) developed a nonlinear model to estimate turbine thermodynamic behavior. Normally, calculation difficulties with non-linear models can not be avoided for greater accuracy.

This work has developed a new model based on thermodynamic principles and semi-empirical equations to estimate steam turbine performance accurately at full-load and part-load operation, and exams the effect of structural parameters (turbine size and type) and operating parameters (turbine steam flow, temperature and pressure, single or multi exhaust rate and pressures) on turbine power generation. The model is verified by commercial turbines and literatures, and applies in a system design and operational optimization allowing for steam mains variation directly.

2. A new steam turbine performance model and efficiency correlation analysis

Steam turbine performance can be expressed by the Willans' line in Eq(1). Parameters *n* and W_{INT} are the slope and intercept of the Willans' line. The deduction of coefficients *n* and W_{INT} mainly were based on steam saturation temperature drop across a turbine in previous models. However, more important operating parameters and equipment size will affect *n* and W_{INT} in the model.

$$W = n \cdot m - W_{\mathrm{INT}} \tag{1}$$

2.1 A new turbine model derivation

Assuming the intercept point to be proportional to the maximum power (Varbanov, et al, 2004), and *a* is the model coefficient in Eq(2).

$$W_{\mathrm{INT}} = a \cdot W_{\max} \tag{2}$$

At full load operation, Eq.1 and Eq.2 can be combined to obtain $W_{\max}$:

$$W_{\max} = \frac{n \cdot m_{\max}}{1+a} \tag{3}$$

Based on the definition of steam turbine efficiency η_{st} in Eq.4, the maximum power generation is calculated by Eq.5. The model coefficient *b* is equal to η_{st} at the maximum load.

$$\eta_{\mathrm{ST}} = \frac{W}{W_{is}} = \frac{W}{\Delta H_{is} \cdot m} \tag{4}$$

$$W_{\max} = \eta_{ST} \cdot m_{\max} \cdot \Delta H_{is} = b \cdot m_{\max} \cdot \Delta H_{is} \tag{5}$$

$$b = \eta_{ST\max} \tag{6}$$

Substituting Eq(5) into Eq(2), W_{INT} can be derived by coefficients *a* and *b*:

$$W_{INT} = ab \cdot m_{\max} \cdot \Delta H_{is} \tag{7}$$

Combine Eq(3) and Eq(5),n is expressed by model coefficients *a* and *b*:

$$n = b(1+a) \cdot \Delta H_{IS} \tag{8}$$

Thus, the steam turbine performance model at part load operation is expressed in Eq(9):

$$W = b(1+a) \cdot \Delta H_{is} \cdot m - ab \cdot \Delta H_{is} \cdot m_{\max} \tag{9}$$

2.2 The correlation between turbine efficiencies and the performance model

Practical power generation is only a fraction of ideal power generation by an isentropic expansion. The remaining power is in the form of mechanical loss, which are quantified by turbine isentropic efficiency η_{is} and turbine mechanical efficiency η_{mech}. As shown in Eq(10), steam turbine efficiency η_{st} is the product of η_{is} and η_{mech}. Normally, a large size turbine has a higher efficiency at full load. The total efficiency falls at part load operation.

$$\eta_{\mathrm{ST}} = \eta_{\mathrm{is}} \cdot \eta_{\mathrm{mech}} \tag{10}$$

η_{is} is the ratio of actual enthalpy drop to the ideal, or isentropic enthalpy drop at the same inlet condition.

$$\eta_{\text{is}} = \frac{\Delta H}{\Delta H_{is}} \tag{11}$$

The variation of turbine efficiency with load can be predicted by the turbine performance model by substituting Eq(9) into Eq(4):

$$\eta_{\text{ST}} = b(1+a) - \frac{ab \cdot m_{\max}}{m} \tag{12}$$

If the mechanical efficiency is known, the variation of turbine isentropic efficiency with operating load can be predicted by turbine model coefficients *a* and *b*:

$$\eta_{is} = \frac{\Delta H}{\Delta H_{is}} = \frac{W}{m \cdot \eta_{mech} \cdot \Delta H_{is}} = \frac{b(1+a) \cdot m - ab \cdot m_{\max}}{m \cdot \eta_{mech}} \tag{13}$$

2.3 Model coefficients

The turbine performance is determined by turbine type, size, turbine steam rate, steam inlet pressure and temperature, and exhaust pressure. The operating parameter of turbine steam temperature T_{in} is accounted for indirectly through ΔH_{is} in Eq(9). Turbine steam pressure P_{in} and exhaust pressure P_{out} determine turbine performance indirectly in Eq(9) through model coefficients and ΔH_{is}. The forms of the correlations for coefficients *a* and *b* are given in Eq(14) and Eq(15), where a_1 to a_4 and b_1 to b_4 are modelling coefficients.

$$a=a_1+a_2P_{\text{in}}+ a_3P_{\text{out}} +a_4P_{\text{in}}P_{\text{out}} \tag{14}$$

$$b=b_1+b_2P_{\text{in}}+ b_3P_{\text{out}} +b_4P_{\text{in}}P_{\text{out}} \tag{15}$$

Coefficients $a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4$ are regressed with commercial steam turbine data at the maximum load and part load.

Steam turbine modelling coefficients are listed in Table 1. The coefficients are different for two turbine types and two sizes: larger back-pressure turbine ($W_{\max}$≥ 5 MW) and smaller back-pressure turbine ($W_{\max}$< 5 MW); larger condensing turbine ($W_{\max}$≥ 20 MW) or smaller condensing turbine ($W_{\max}$< 20 MW).

2.4 Models validation and error analysis

The new model is validated by the literatures (Flores and Nunez, 2010) shown in Table 2, and other 3 commercial turbines from Varbanov et al. (2004) shown in Table 3. From Table 2 and Table 4, the new proposed model estimates power generation with high accuracy, giving the error of power less than 1 %.

Table 1: Steam turbines modelling coefficients

	Back-pressure turbines		Condensing turbine	
	$W_{\max}$ <5MW	$W_{\max}$ ≥5MW	$W_{\max}$ <20MW	$W_{\max}$ ≥20MW
a_1	0.19661	0.16378	0.00321	0.24597
a_2	-0.00056	-0.00042	-0.00031	-0.00100
a_3	0.00016	0.00321	0.45489	-2.48144
a_4	0.00002	-0.00001	0.00346	0.02888
b_1	0.77684	0.83231	0.74791	0.80426
b_2	-0.00063	-0.00037	0.00065	-0.00004
b_3	-0.00522	-0.00471	0.56224	0.17584
b_4	0.00004	0.00003	-0.00881	0.00098

Table 2: Comparisons of steam turbine performance models

Model	ST1		ST2		ST3	
	W_{cal} (MW)	Error (%)	W_{cal} (MW)	Error (%)	W_{cal} (MW)	Error (%)
Mavromatis and Kokossis (1998)	10.7	-2.8	25.15	0.59	2.72	-10.29
Varbanov et al. (2004)	11.77	6.54	26.81	6.75	3.17	5.36
Flores and Nunez (2010)	10.97	0.27	25.04	0.16	3.00	0
The proposed model	10.91	0.78	25.13	0.50	2.97	0.90

Note: Turbine data are from literature (Flores and Nunez, 2010)

Table 3: Commercial steam turbine data (Varbanov et al., 2004)

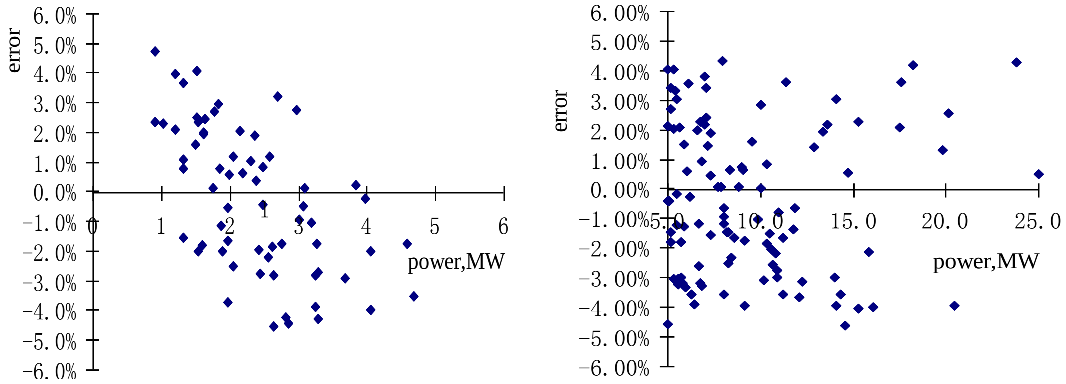
Turbine	T_{in} (°C)	P_{in} (MPa)	m (kg/s)	P_{out} (MPa)	W (MW)
ST4	425	12	22.71	1.0	8.987
ST5	300	1.48	36.63	0.18	11.875
ST6	380	6.0	27.59	1.0	8.013

Table 4: Model validation for commercial turbines

Model	Turbine 4		Turbine 5		Turbine 6	
	W_{cal} (MW)	Error (%)	W_{cal} (MW)	Error (%)	W_{cal} (MW)	Error (%)
Varbanov et al. (2004)	8.030	-10.65	9.795	-17.5	6.731	-15.99
Flores and Nunez (2010)	9.197	2.34	12.789	7.7	8.808	6.68
Proposed models	9.052	0.72	11.796	0.66	7.940	-0.91

Note: Commercial turbine data shown in Table 3 are from Varbanov et al. (2004)

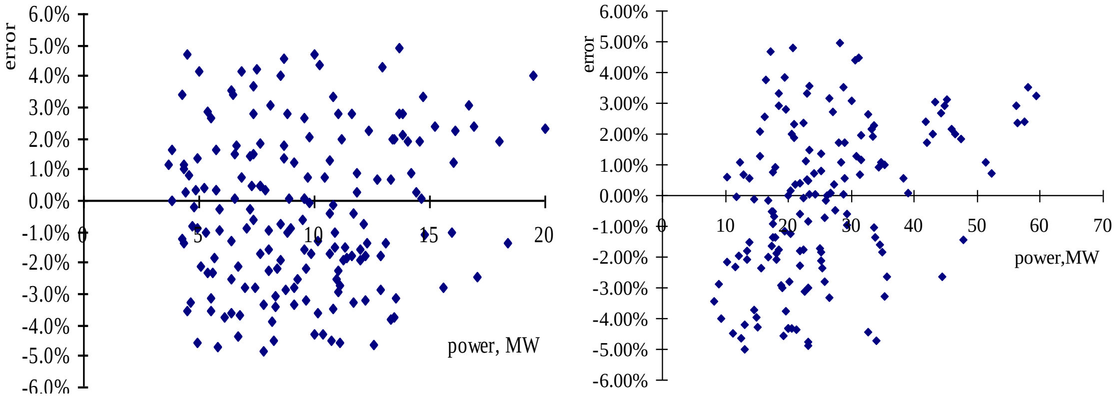
These modelling coefficients have been fitted to a large number of commercial turbines (Varbanov, 2004) at full-load and part-load operations. Figure 1 presents the deviation of power estimation comparing with 70 back-pressure turbine design data(turbine sizes: 1 MW to 35 MW) at 214 operating states (operating load: 40 % to 100 %), giving a mean error of power prediction of 2.2 % for the proposed back pressure turbine model. Figure 2 illustrates the error distribution of power prediction for 104 condensing turbines (turbine sizes: 8 MW to 60 MW) at 335 operating conditions states (operating load: 40 % to 100 %). The mean error is 2.1 % for the condensing turbine model.



Power<5MW

Power≥5MW

Figure 1: Back-pressure steam turbine model error analysis



Power<20MW

Power≥20MW

Figure 2: Condensation turbine model error analysis

This deviation analysis demonstrates that the new model is consistently accurate for a wide range of turbines, allowing for steam heads variation directly.

3. Steam turbine model application

Utility system optimization has been carried out the proposed turbine performance model for both design and operation problem. The turbine model for single-stage turbines can be extended to multi-stage turbines.

As shown in Figure 3, a multi-stage turbine can be modeled as a set of single-stage turbines in series. The efficiency estimation method of a single-stage turbine and a multi-stage turbine are similar.

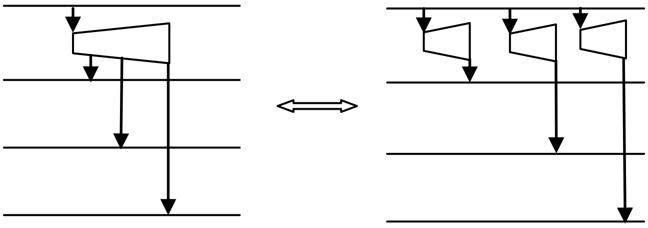


Figure 3: A complex multi-stage turbine equivalents to several single-stage turbines

3.1 Utility system design

The turbine prerformance model can model a large range of steam turbines at full-load and part-load operation with good accuracy. It is primarily intended to be employed for utility system design and optimizaton without initial information about any particular steam turbine choice, to obtain an initial system configuration.

3.2 Operational optimization and system retrofit

The new model can be applied in operational optimization and system retrofit including complex turbines. It overcomes problems in operational optimization from previous models, which did not account for changes in steam mains pressures.

Actual turbine operation normally is far away from the design condition because of process parameter adjustments and utility system variations. For example, the input steam pressure fluctuation is common in the turbine operation. From the Enthalpy- Entropy analysis, input steam pressure rise would lead to higher turbine efficiency. Thus, turbine model coefficients should be regressed based on turbine operational data for retrofit problem. Two criteria are followed for the coefficient regression:

$$\min\,(W_{\mathrm{cal}}-W_{\mathrm{real}}) \tag{16}$$

$$\min\,(T_{\mathrm{out\ cal}}-T_{\mathrm{out\ real}}) \tag{17}$$

4. Conclusions and discussions

A new steam turbine model has been developed and verified to provide accurate prediction of turbine performance, particularly the prediction of power production at part-load. The coefficients in the proposed model are determined by key operating parameters like turbine steam flow rate, steam temperature and temperature, and turbine exhaust pressure. Turbine structural parameters such as turbine size and type are included in the performance model.

The high accuracy of the proposed model for steam turbine performance estimation of different types and wide range of sizes can lead to reliable initial new turbine system design. It is also applied in existing design for retrofit and operational optimization of an exist design allowing for changes in steam header conditions. Furthermore, the coefficient regression of the turbine performance model according to turbine operational data leads to more accurate power predictions in the operational optimization.

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Nomenclature

a - steam turbine model coefficient
b - steam turbine model coefficient
η_{ST} - overall steam turbine efficiency
η_{is} - turbine adiabatic efficiency
η_{mech} - mechanical efficiency
H_{in}- specific enthalpy of the inlet steam, $kJ{\cdot}kg^{-1}$
H_{out}- specific enthalpy of the outlet steam, $kJ{\cdot}kg^{-1}$
H_{is}- enthalpy of steam at the outlet pressure having the same entropy as the inlet steam, $kJ{\cdot}kg^{-1}$
ΔH- the enthalpy drop, $kJ{\cdot}kg^{-1}$
ΔH_{is} - the isentropic enthalpy drop across the turbine, $kJ{\cdot}kg^{-1}W$
m_{max}- turbine maximum steam flow, $kg{\cdot}s^{-1}$
m - turbine steam flow, $kg{\cdot}s^{-1}$
n - the slope of Willians' line, $kJ{\cdot}kg^{-1}$
P_{in} - the inlet steam pressure of steam turbine, kPa
P_{out} - the extraction steam pressure of steam turbine, kPa
T_{in} - the inlet steam temperature, °C
T_{out} - the extraction steam temperature, °C
W - turbine shaft power, kW
W_{max} - turbine shaft power at maximum load, kW
W_{IS} - steam turbine shaft power in corresponding with an isentropic expansion, kW
W_{INT} - intercept of the linear Willians' line, kW

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