# Sliding Pressure Optimization Method for Steam Turbine with Main Steam Flow Rate as Independent Variable

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***Abstract* — Large power units have to run under deep variable load operations to reduce the regulation peak of power systems. The sliding pressure operation is now recognized as one of the most effective ways to improve economy and safety at variable load operations. In this paper, we examine the effects of back pressure and steam extraction on the optimum sliding pressure operation curve and analyze the limitations of the traditional sliding pressure operation curve design methods. Consequently, we propose a new optimization method for the sliding pressure operation that uses the main steam flow rate as an independent variable. Our results show that the sliding pressure operation curve obtained via the proposed method can overcome the effect of the heating steam extraction capacity and back pressure on the unit. The proposed method also satisfies the economic operation in different working conditions, and can easily be implemented in the Distributed Control System (DCS) transformation. Optimization transformation of the variable load running economy by application of the method in an air-cooled unit resulted in significant improvement. It significantly enhances the safety and efficiency of thermal power generating units, which are dominant in China.**

***Keywords - Turbine; back pressure; extraction; main steam flow; sliding pressure; optimization;***

## I. INTRODUCTION

Large-scale new-energy integrations such as wind power currently have a negative effect on existing power systems because of the strong stochastic volatile uncertainty of the new energy [1, 2]. Consequently, large thermal power units for rapid depth variable load involved in peak load operation are imperative, which results in many problems affecting safe and efficient operation of the units [3, 4]. In addition to condensing thermal power, many cogeneration units should also be involved in peaking depth [5]. The sliding pressure operation is now recognized as one of the most effective means of improving the economy and security of units in part load operating conditions [6–9].

The sliding pressure operation is safer and more economical than the constant pressure operation. For example, the sliding pressure operation can reduce throttling losses, improve high-pressure cylinder internal efficiency, reduce feed pump power consumption, improve low-load thermal effi[1]ciency, reduce thermal stress and thermal deformation, and improve the reliability and load adaptability of the unit[10-16].

The sliding pressure operation curve is used extensively nowadays. It typically takes the unit load as an independent variable to determine the main steam pressure. It is well known that there are many factors that significantly affect the unit load, such as the back pressure of the air-cooling unit and extraction of the heat extraction unit. In engineering practice, the coefficient modification method, for which determination is complicated and impractical, is the main optimization method used with the sliding pressure curve. For example, it modifies the sliding pressure operation curve of the extraction unit because of a normal condition that is not applicable for other conditions. Therefore, the method used for sliding pressure operation curve determination is inadequate.

In this paper, we discuss the limitations of the traditional sliding pressure operation curve design and implementation method from the point of view of back pressure steam and steam extraction, and subsequently propose a new sliding pressure curve computation method based on main steam flow. We also verify that the optimal main steam pressure is a single-valued function of the main steam flow from both theoretical and experimental analyses, and prove the validity of the proposed sliding pressure curve determination method.

The sliding pressure operation curve determined by the new method can satisfy various conditions, decrease the difficulty of field operations, and improve the unit economy. In this paper, we show that the variable load economy of an air-cooled unit is significantly improved after application of

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this proposed optimization method.

## II. LIMITATION OF THE CLASSICAL SLIDING PRESSURE OPERATION CURVE

A variety of factors should be comprehensively considered in the optimal sliding pressure operation curve design. There is currently a limitation on the sliding pressure optimization method with the unit load independent variable. Owing to many influencing factors on the unit load, such as the back pressure and extraction heating, which can significantly change the unit load, the sliding pressure operation curve deviates from design conditions. Although a correction coefficient is used in engineering practice, determination is more complex, and the problem has not been completely solved.

### *A. Influence of Black Pressure*

Among all the thermal parameters of the turbine, the back pressure is one of the most influential on the unit economy. Back pressure changes influence not only the turbine power, but also the turbine rotor time constant and the speed variation rate of the speed governing system. Whereas other operating parameters remain unchanged at steam valve adjustment, the power turbine declines and the speed variation rate increases with the back pressure rising. Under the influence of the unit load, circulating water flow, circulating water inlet temperature, condenser cleanliness, vacuum tightness, structural characteristics of the condenser and the exhaust, and many other factors, the running back pressure changes frequently, thus affecting the crew economy.

The direct air-cooling unit is affected by the refluxing hot summer wind; thus, the unit back pressure is very sensitive to wind speed and direction. Along with the environmental temperature, the effect of wind speed and wind direction is significant, as shown in Figure 1.

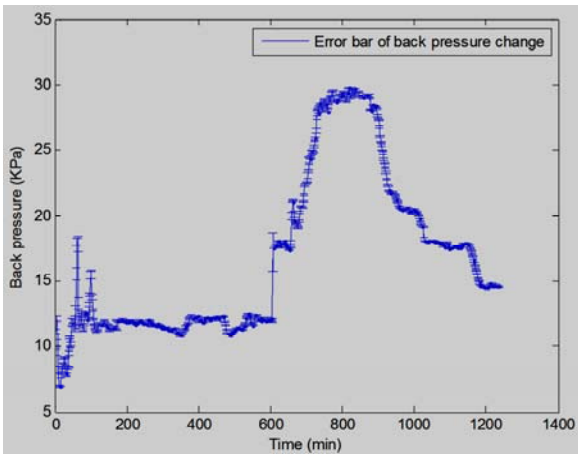

Fig.1 Back Pressure Change of a 300 MW Air-cooling Unit

The power changes caused by the back pressure are analyzed in Figure 2. Back pressure 1 is greater than back pressure 2; enthalpy drop 1 is less than enthalpy drop 2; and power 1 is less than power 2. While other operating parameters remain unchanged, at the same control valve opening, the turbine power is reduced with the back pressure rising, and the power increases. This can be observed directly from the enthalpy drop change.

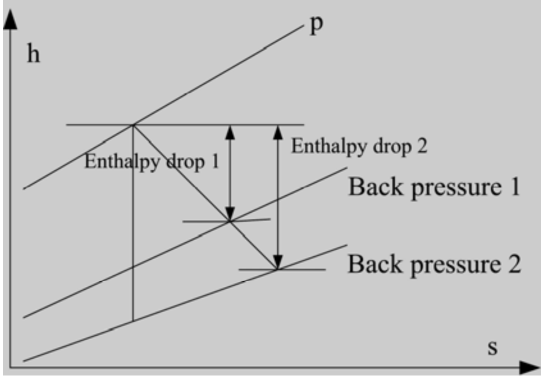

Fig.2 Power Change Induced by The Back Pressure

Each back pressure corresponds to a unit load. When the unit load is regarded as the independent variable to determine the sliding pressure curve of the unit, a back pressure will correspond to a sliding pressure curve. Therefore, the sliding pressure curve will be a group rather than a single one, and so the graph becomes a two-dimensional map. Consulting the graph and taking the load as the independent variable to determine the optimal value of the sliding pressure is inconvenient. In this case, the optimal main steam pressure is a function of the load and back pressure; that is, optimal main steam pressure = F(load, back pressure), as shown in Figure 3.

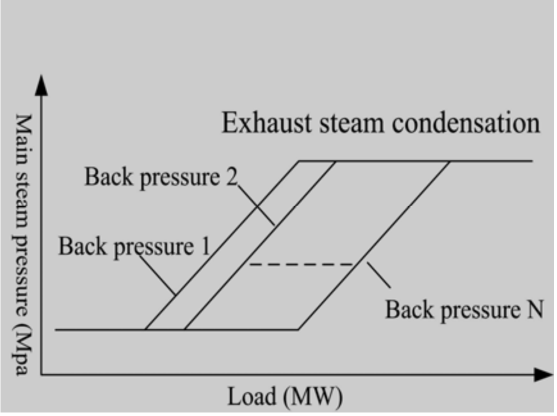

Fig.3 Sliding Pressure Curves of Condensing Generation Units

### *B. Influence of Extraction Steam*

Determination of the optimum sliding pressure curve for the extraction steam turbine is more complicated than for the condensing reheat steam turbine. This is mainly because of the following factors:

(1) When the heat supply unit is operating in extraction mode, the extraction pressure is determined by the user of the heat and the extraction point pressure is constant. Therefore, the extraction point pressure remains unchanged while the working conditions of the unit are changing.

(2) The working conditions of the heating supply unit in a non-steam extraction mode are similar to that of the reheat steam unit. Therefore, the heating extraction point pressure changes with the unit condition.

Consequently, there is a significant difference in the operating condition characteristics of the stage group and the regenerative heater variable when the heating unit is operating in extraction conditions and non-extraction mode.

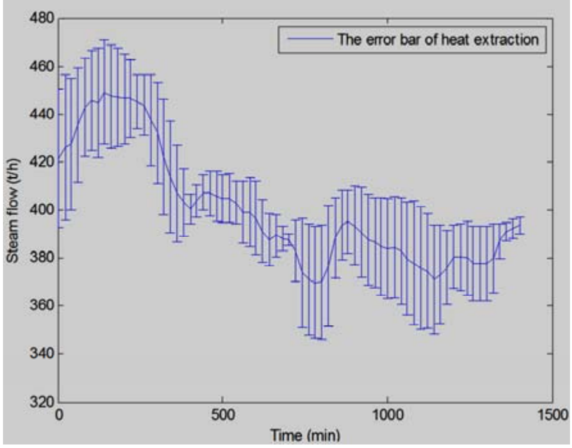

Fig.4 Heat Extraction Variation of a 300 MW Unit

When the unit load is regarded as the independent variable to determine the sliding pressure curve of the unit, the impact of back pressure and extraction flow for the extraction unit must be considered; specifically, optimal main steam pressure = F(load, back pressure, steam extraction). With this condition, the sliding pressure graph becomes a three-dimensional map, as shown in Figure 5, which is more complex than for the non-steam extraction unit. Determining the optimal sliding pressure value according to the current method is unreliable. This simple method of determining sliding pressure curves is not optimal when the unit is in a variable condition.

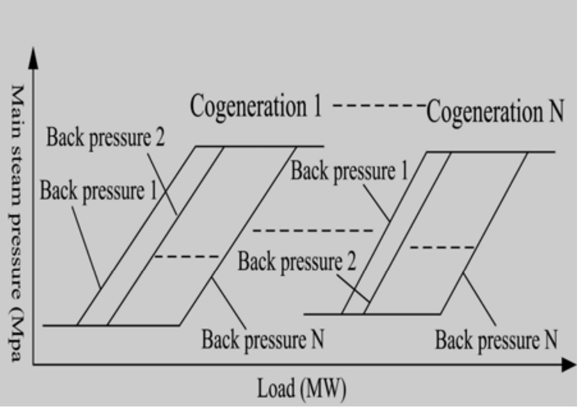

Fig.5 Sliding Pressure Curves with Different Extractions

## III. LIDING PRESSURE OPERATION OPTIMIZATION WITH MAIN STEAM FLOW INDEPENDENT VARIABLE

The main steam flow is in fact a factor that directly affects sliding pressure curve determination. Thus, a sliding pressure optimization method based on the main steam flow as the independent variable, is feasible both from theoretical and practical aspects.

### *A. From the Viewpoint of the Pump Power*

The feed pump power formula [17] is defined by equation (1):

$$P_{gs} = \frac{G_0 \bar{v}(p_0 - p_{gs})}{\eta_p} \tag{1}$$

where $p_0$ is the main steam pressure, $p_{gs}$ is the pressure before the feed pump, $G_0$ is the feed water flow, $\bar{v}$ is the specific volume, $\eta_p$ is the feed pump efficiency, and $P_{gs}$ is the feed pump dissipation.

In the actual power generation process, the feed pump power is determined by the main steam flow, $G_0$, and the main steam pressure, $p_0$, because the pressure before the feed pump, the specific volume, and the feed pump efficiency are virtually constant. Consequently, the feed pump power is a function of the steam flow and the main steam pressure; that is, $P_{gs}=f(G_0,p_0)$.

### *B. From the Viewpoint of the Unit Power*

(1) The regulating valve throttling loss

The regulating valve throttling loss is the difference in value between the steam pressure and the pressure before the regulating stage. This is given by the Frugal formula [18]:

$$\frac{D'}{D_0} = \sqrt{\frac{T_1}{T_1'}}\sqrt{\frac{p_1'^2 - p_z'^2}{p_1^2 - p_z^2}} \tag{2}$$

where *D*' is the main steam flow after the variable condition; $D_0$ is the main steam flow before the variable condition; $T_1$' is the main steam temperature after the variable condition; $T_1$ is the main steam temperature before the variable condition; $p_1$' is the governing stage anterior pressure before the variable condition; $p_1$ is the governing stage anterior pressure after the variable condition; $p_z$' is the back pressure after the variable condition; and $p_z$ is the back pressure before the variable condition;

The Frugal formula is suitable for more than five stages and constant flow areas; therefore, the flow passage between the governing stage anterior pressure and the back pressure is the analytical subject of the variable condition. According to formula (2), the governing stage anterior pressure change is related with the change in the steam flow, the steam pressure, and the back pressure. In the actual power generation process, the change in the main steam temperature before the variable condition can be omitted, and the square of the back pressure, $p_z^2$ relative to the square of the governing stage anterior pressure, is negligible. Thus, the Frugal formula can be simplified to $\frac{D_0'}{D_0}=\frac{p_1'}{p_1}$. The regulating valve throttling loss is only a function of the main steam flow and the main steam pressure; that is, $\Delta p=f(G_0,p_0)$.

(2) Relative internal efficiency of the governing stage

Assuming that the main steam flow is constant, the pressure after the governing stage remains constant, as can be seen from the Frugal formula. The flow area is constant, and the difference between the throttling pressure and the governing stage pressure remains unchanged; thus, the throttle pressure is a fixed value, and actual enthalpy drop is certain. The main steam temperature remains approximately constant at 538 ℃; the main steam enthalpy is a function of the main steam pressure.

Therefore, the ideal enthalpy drop of the governing stage is a function of the main steam pressure. It is clear that when the main steam flow is constant, the power before the governing stage is a fixed value, and efficiency is only related to the main steam pressure. In conclusion, it is obvious that the work of the governing stage is included when the sliding pressure setpoint of the main steam pressure is determined with the main steam flow independent variable.

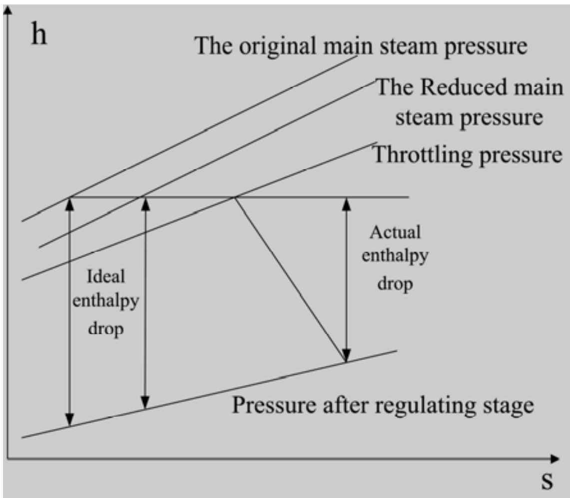

Fig.6 Enthalpy-entropy Figure before Governing Stage

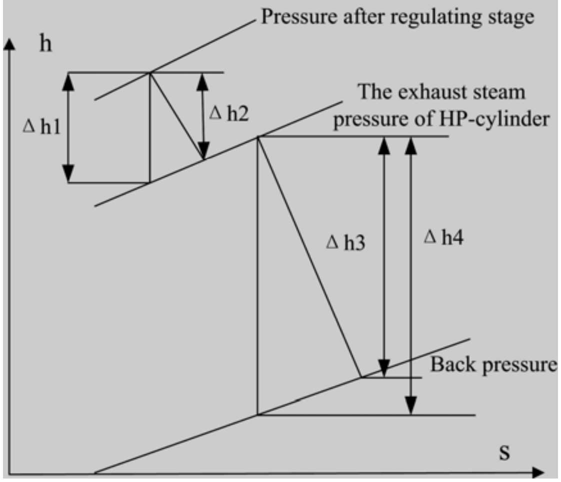

Fig.7 Enthalpy-entropy Figure with Constant Back Pressure after Governing Stage

(3) Internal efficiency of the high-pressure cylinder

Let us first consider the condition with the unchanged back pressure. Assuming that the main steam flow is constant, the change in the main steam pressure may cause the high exhaust temperature to fluctuate, as illustrated in Figure 7. Because the magnitude of the fluctuations is not significantly changed, the high exhaust pressure line and the back pressure line are approximately parallel in a small range of the high enthalpy-entropy diagram, which shows Δh3 and Δh4 as unchanged in essence, while Δh1 and Δh2 remain constant when the high exhaust temperature changes. Therefore, the power and efficiency after the governing stage are approximately unchanged when the back pressure is certain.

Let us now consider the condition of the back pressure variation. From the above analysis, the high exhaust temperature can be ignored, resulting in the enthalpy-entropy figure shown in Figure 8. In this case, only the power after the governing stage will change with the back pressure variation. There is no effect on the determination of the optimal main steam pressure; thus, the impact of the back pressure can be ignored during determination of the optimal main steam pressure. The figure illustrates that the unit power is only affected by the main steam pressure when the main steam flow is certain. Further, the effect of the working unit is included when the sliding pressure set point of the main steam pressure is determined with the main steam flow independent variable.

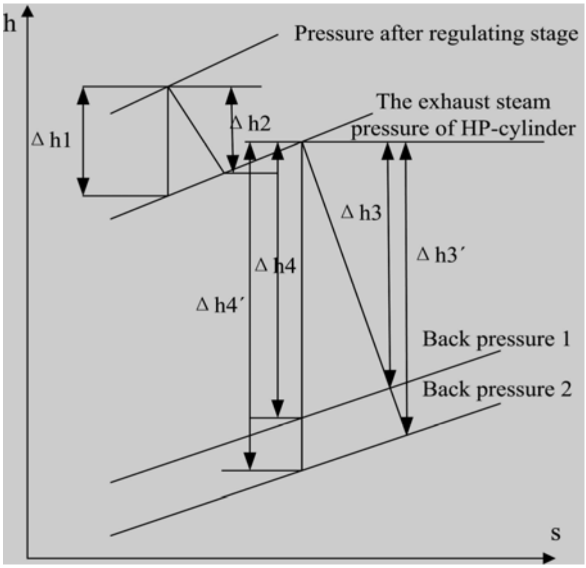

Fig.8 Enthalpy-entropy Figure with Varied Back Pressure after Governing Stage

### C. *From the Viewpoint of The Heat Rate Calculation*

The method used to determine the sliding pressure curve according to the main steam flow is based on the heat rate calculation for the theoretical basis. Therefore, the correctness of the new method is studied from the perspective of the heat rate calculation. The unit heat rate is typically calculated with the ASME PTC6-1996 and ASME PTC6-1982 methods [19]. A simplified formula for the heating unit heat rate is as follows:

$$\mathrm{H_{rt}} = ( Q_{gs} + Q_{zr} - Q_{cq})/( P_g + P_{zd}) \tag{3}$$

where $Q_{gs}$ is the steam absorbed heat in the boiler; $Q_{zr}$ is the steam absorbed heat in the reheater; $Q_{cq}$ is the extraction heating heat transfer; $P_g$ is the high-pressure cylinder work; and $P_{zd}$ is the middle and lower pressure cylinder work.

From the above equation, the high-pressure cylinder work, $P_g$, is constant when the main steam flow is certain. The steam absorbed heat in boiler $Q_{gs}$ and the steam absorbed heat in reheater $Q_{zr}$ are single-valued functions of the main steam pressure, $p_0$. The extraction heating heat transfer $Q_{cq}$ and the middle and lower pressure cylinder work $P_{zd}$ are constant with the given extraction and back pressure, which are unaffected by the main steam pressure, $p_0$.

Thus, the heat rate, $H_{rt}$, is the main single-valued function of the main steam pressure, $p_0$. The formula thus becomes

$$H_{rt}(p_0) = \frac{Q(p_0) - Q_{cq}}{P_g + P_{zd}} \tag{4}$$

In equation (4), the heat rate is a function of the main steam pressure, $H_{rt}$ $(p_0) = f$ $(p_0)$. Determination of the optimal main steam pressure equates to finding the main steam pressure, $p_0$, with the minimum heat rate, $H_{rt}(p_0)$. It is clear from the equation that the minimum of the main steam pressure, $p_0$, should be found with the minimum $Q(p_0)$, which is the optimal value.

When the main steam flow remains constant and changes are made to the heat extraction and back pressure, the high-pressure cylinder work, $P_g$ , still remains at the original value, and the steam absorbed heat in boiler $Q_{gs}$ and steam absorbed heat in reheater $Q_{zr}$ are still single-valued functions of the main steam pressure, $p_0$. The extraction heating heat transfer, $Q'_{cq}$, and the middle and lower pressure cylinder work, $P'_{zd}$, are constant according to the changed heat extraction and back pressure, which are still unaffected by the main steam pressure, $p_0$. At this point, the heat rate, $H_{rt}(p_0)'$, is still the main single-valued function of the main steam pressure, $p_0$. The formula consequently becomes

$$H_{rt}(p_0)' = \frac{Q(p_0) - Q_{cq}'}{P_g + P_{zd}'} \tag{5}$$

Equation (5) shows that the heat rate, $H_{rt}(p_0)'$, is a function of the main steam pressure, $p_0$. Further, $H_{ri}$ $(p_0)' = f$ $(p_0)$ indicates that the optimal main steam pressure determination still equates to finding the main steam pressure, $p_0$, with the minimum heat rate, $H_{rt}(p_0)'$, and also to finding the main steam pressure, $p_0$, with the minimum heat rate, $Q(p_0)$.

In addition, regardless of any heat extraction and back pressure changes that may occur, the minimum value of $Q(p_0)$ determination will not be affected; therefore, there is no influence on the optimal main steam pressure, $p_0$, determination. Finally, because the main steam flow is constant, regardless of the change in the heat extraction and back pressure, only a fixed optimal main steam pressure can result, there is only one optimal value for the main steam pressure, $p_{best}$. This is a single-valued function of the main steam flow $D_0$, $p_{best}=f(D_0)$, but independent of heat extraction and back pressure. Therefore the effects of the heat extraction and back pressure are included in the sliding pressure curve determination method with the main steam flow independent variable. The validity of this method has already been demonstrated above.

### *D. From the Viewpoint of Steam Extraction and Back Pressure*

Steam extraction changes can only influence the governing stage power. Further, it has been demonstrated that the governing stage power change will not have an impact on determination of the optimal sliding pressure value, which illustrates that the effects of steam extraction can be ignored when the sliding pressure curve is determined with the main steam flow independent variable on the condition that the main steam flow is certain. By the same analysis, the method used to determine the sliding pressure curve is also reasonable when the back pressure changes.

## IV. THE OPTIMAL SLIDING PRESSURE CURVE ACQUISITION METHOD

Currently, the function for checking the value in most power plants is suitable only for one-dimensional graphs—two- and three-dimensional graphs can only be treated as one-dimensional with this function. Therefore, the method used to determine the optimal sliding pressure value with the unit load independent variable applies only to a certain back pressure and a certain steam extraction. If the back pressure and steam extraction values of the actual working condition have deviations from these values, the sliding pressure values are not optimal.

In order to find the optimal sliding pressure values for each condition, in this paper, an integrated sliding pressure curves optimization method that takes the back pressure and extraction steam as correction parameters, by which the sliding pressure graph is approximately a one-dimensional figure, is proposed.

The acquisition method is as follows:

(1)Select M main steam flows, ordering from small to large according to the type of heat extraction unit, where M is an integer greater than four. Perform Steps 2 through 4 for every main steam flow, then Step 5.

(2)With the selected main steam flow, and the heat steam extraction and condenser vacuum remaining unchanged, select N different main steam pressure values for the heat extraction unit according to the main steam flow; N is an integer greater than four.

(3)Retain the main steam flow unchanged in each of the main steam pressures, and calculate the heat consumption values corresponding to the main steam pressure.

(4)Fit the N main steam pressures and their corresponding heat consumption values using the least squares curve fitting method, with the lowest point on the curve representing the lowest point of the heat rate. Thereby, determine the optimal unit main steam pressure value with the main steam flow, as shown in Figure 9.

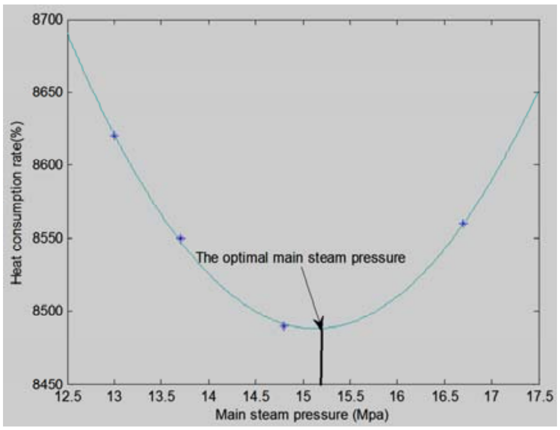

Fig.9 Fitting Curve of Steam Pressure and Heat Rate

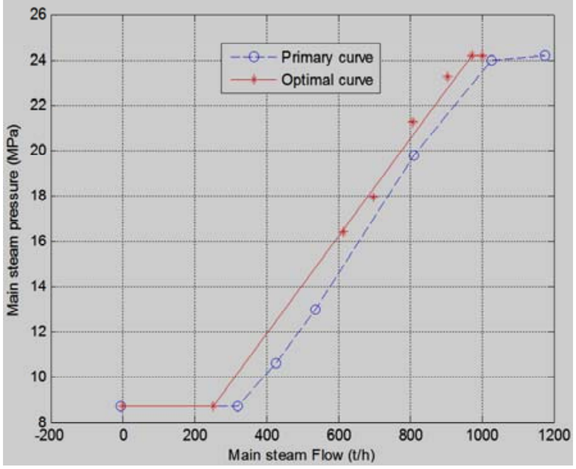

Fig.10 Sliding Pressure Curves Comparison Pre- and Post-optimization

(5)Obtain the final curve by linear fitting for M main steam flow values and their corresponding optimal main steam pressure data.

Using the steps above, the sliding pressure curve can be obtained with the main steam flow as an independent variable.

The sliding pressure operation optimization for a 350 MW supercritical air-cooling unit is shown in Figure 10. The curves between pre- and post-optimization with the main steam flow as independent variable are given. The unit economy comparisons pre- and post-optimization are shown in Table I. It is clear that the new optimization method can improve the unit economy.

## V. CONCLUSION

On the basis of the influence of steam extraction and back pressure on the sliding pressure operation curve, the limitations of the sliding pressure optimization method adopted by domestic power plants were presented. Consequently, a new sliding pressure operation curves optimization and acquisition method with the steam flow as an independent variable was proposed. The efficacy of the proposed method was proved through theoretical and experimental research.

For an air-cooled unit, the influence of the back pressure change on the sliding pressure operation curves using the new method decreases, and the unit economy can be improved under variable conditions.

For an extraction steam unit, using the new optimization method, the sliding pressure curve is suitable for extraction and non-extraction operation modes, which can meet the demands of the sliding pressure operation economy in both modes.

For the units with changing extraction and back pressure, the new method can avoid their influences on the sliding pressure operation economy.

TABLE I. UNIT ECONOMY COMPARISONS PRE- AND POST-OPTIMIZATION

| Condition | Main steam flow（t/h） | Optimized main steam pressure（MPa） | Optimized heat rate（kJ/kw·h） | Main steam pressure before optimization（MPa） | Heat rate before optimization（kJ/kw·h） | Difference in heat rate（kJ/kw·h） |
|---|---|---|---|---|---|---|
| 1 | 622.62 | 16.29 | 9129.35 | 15.11 | 9227.82 | 98.47 |
| 2 | 700.25 | 18.08 | 8984.15 | 16.99 | 9050.50 | 66.35 |
| 3 | 812.83 | 21.19 | 9012.74 | 19.71 | 9114.88 | 102.14 |
| 4 | 912.33 | 23.31 | 8854.37 | 21.64 | 8965.06 | 110.70 |
| 5 | 997.13 | 24.20 | 8848.30 | 23.27 | 8884.32 | 36.02 |
| Mean heat rate：82.73（kJ/kw·h） | | | | | | |

## CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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