sHeat transfer and optimization of thermal systems

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Abstract:

In view of reform electricity policies, increasing demand, competitive market and rapid change of the world scenario it is vital to make the necessary changes in power sectors at all levels. Optimization is one of the techniques to operate any system in most efficient manner as per need. Thermal power plant, a major source of power generation encounters mainly three types of irreversibility.

Heat transfer irreversibility through hot end heat exchanger and cold end heat exchanger has the major effects on power plant. These can be minimized by optimization of size of heat exchangers, optimum distribution of investment in external conductance and internal resistance,minimum heat exchanger inventory, optimum allocation of heat exchanger equipment etc.

It is observed that in a 540 MW power plant, which is handled by 'Jacob Consultancy', a change in cooling water flow rate, cooling the condenser of a power plant causes changes in condenser pressure and exhaust losses of steam turbine and has a significant impact on plant performance.

In the present paper, various optimization aspects are discussed in much elaborated manner with suitable example.

Keywords: Heat transfer irreversibility, Optimization.

Nomenclature:

$\dot{Q}_{HC}$: Heating rate to the reversible part of the power plant
$\dot{Q}_{LC}$: Heat rejection from the reversible Part of the power plant
C_H : External conductance of hot-end heat exchanger.
C_L : External conductance of cold-end heat exchanger.
T_H : High temperature
T_L : Low (ambient) temperature.
T_{HC} : High temperature experienced by the reversible part of power plant
T_{LC} : Low temperature experienced by the reversible part of power plant
$\dot{Q}_i$: Internal heat leak
C_i : Internal conductance
$\dot{W}$: Power output
x : External conductance allocation ratio
τ : Temperature ratio, (T_H / T_L)
C_e : Total external conductance inventory
τ_c : Carnot temperature ratio
U : Overall heat transfer coefficient based on area A
A : Heat exchanger area
∈ : Temperature ratio, (T_L/T_H)
θ : Temperature ratio, (T_{HC}/T_H)

Introduction

Over the last 5 years, the European power production industry is facing rapid changes. Due to the liberalization of the electricity market, power plants are facing operational requirements that have not been anticipated during their design. Also due to the liberalization, electricity prices are under pressure and power plants receive lower operating incomes.

Optimization is nothing but extracting maximum power, it can be achieved by maintaining proper balance among cooling water temperature, mass flow rate, size of equipment thereby minimizing the installation and operating cost.

Heat transfer irreversibility in thermodynamic plant

The technological developments that led to toady's explosive growth in electrical power production are all manifestations of common design philosophy. There exist three fundamental trade offs in the design of a power plant.

The irreversibility of a steady – state power plant model is due to three sources

1) The hot end heat exchanger

$$\dot{Q}_{HC} = C_H (T_H - T_{HC})$$

2) The cold end heat exchanger and

$$\dot{Q}_{LC} = C_L (T_{LC} - T_L)$$

3) The heat leaking through the plant to the ambient

$$\dot{Q}_i = C_i (T_H - T_L)$$

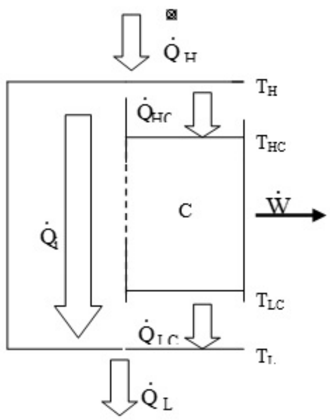

Fig. 1 Power plant model with three sources of heat transfer irreversibility.

Minimization of irreversibility using optimization

The optimum solution for a power plant can be found out with the approach of maximizing power by applying different constraints. The expression for power output $\dot{W}$ is

$$\dot{W} = x(1-x)C_e\left(\frac{\tau}{\tau_c}-1\right)(\tau_c-1)$$

The expression for power output $\dot{W}$ shows that the instantaneous power output per unit of external conductance inventory (C_e = constant) can be maximized in two ways.

Solving first $\delta W/\ \delta\tau_c = 0$, the optimum Carnot compartment ratio is obtained

$$\tau_{c.opt} = \tau^{1/2}$$

Also there exists an optimum way to allocate the C_e inventory between the hot and cold ends such that the power output is maximized once more. Setting the $\delta/\delta X$ derivative of power output $\dot{W}$ yields the optimum external conductance allocation fraction.

$$x_{opt} = \frac{1}{2}$$

Therefore, to operate at maximum power there must not only be a balance between the thermodynamic temperature ratios τ and τ_c but also a balance between the sizes of hot and cold heat exchangers.[1]

Minimum heat exchanger inventory

The optimization principle is 'The needed heat exchanger inventory is minimum when it is dividing evenly between two ends of cycle'.

The heat exchanger sizes are represented by the overall thermal conductance $(UA)_H$ and $(UA)_L$. The analytical statement of the thermal design problem is completed by writing that the total capital investment UA must be minimized

The cost function UA can be written in non-dimensional form

$$\frac{UA}{(\dot{W}/T_H)} = \frac{(\tau-\in)}{(1-\theta)(1-\tau)(\tau\theta-\in)}$$

The expression clearly shows that the design gas two degrees of freedom (τ and θ) which correspond physically to selection $(UA)_H$ and $(UA)_L$

First performing minimization with respect to θ.

$$\theta_{opt} = \frac{\tau+\in}{2\tau}$$

Next by minimizing with respect toτ, we have

$$\tau_{copt} = \in^{1/2}$$

An additional feature of this design point of minimum heat exchange size is $(UA)_H=(UA)_L$. The optimal way of allocating heat exchange inventory UA is by using half of it at hot end and other half at cold end.

The power plant with minimum heat exchanger equipment and fixed power output has same efficiency as the power plant designed for maximum power and that $(UA)_H = (UA)_L$.[2]

"Maasvlakte" thermodynamic plant

In this power plant, the operation of the cooling water system has been optimized based on cooling water temperature and power plant load. For cooling its condenser the Maasvlakte power plant uses cooling water from the entrance of the Rotterdam harbour. The temperature of this cooling water varies from around 1°C in winter up to 25°C in summer.

The cooling water flow rate can be controlled by adjusting the blade angle of the cooling water pumps. Doing so, the cooling water flow rate can be varied between 10 m^3/s and 20 m^3/s. During plant operation, the objective is to operate at the optimum cooling water flow rate from an economic point of view. This optimum, however, is dependent on a number of conditions such as plant load and cooling water inlet temperature.

Cold end optimization

The impact of cooling water flow rate on power plant performance is significant. The optimum amount of cooling water depends primarily on cooling water temperature and power demand. Adequate guidelines on operators how to operate and optimize the cooling water system are valuable tools to increase power plant revenues.

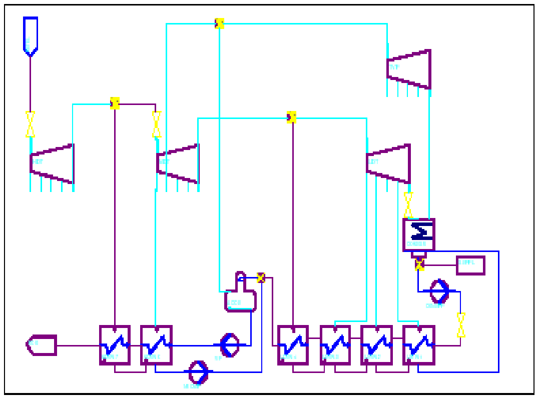

Fig. 2 Thermodynamic plant model "Maasvlakte"

Figure shows the process flow diagram of the plant model that has been set op for power plant "Maasvlakte". In this model, emphasis has been put on modeling the steam turbine, condenser, and feed water train. For this cooling water optimization, the boiler performance was considered to be of less relevance. Therefore, the boiler has not been modeled in detail.

In the project, it is decided to derive polynoms and implement these in the process computer.By calculating performance for several combinations of cooling water flow and cooling water temperature, a set of heat rate curves can be generated as can be seen in figure. In this figure, each curve shows the change of net specific heat rate at a constant cooling water temperature, as a function of cooling water flow rate.

It can be clearly recognized that at each cooling water temperature an optimal heat rate can be reached. It can also be seen that for different cooling water temperatures, different optimal cooling water flow rates exist. Remember this is still at a constant heat input to the steam turbine. The cooling water flow from the optimum heat rate at a given plant load and cooling water temperature can be found by the differentiation of the representative polynom.

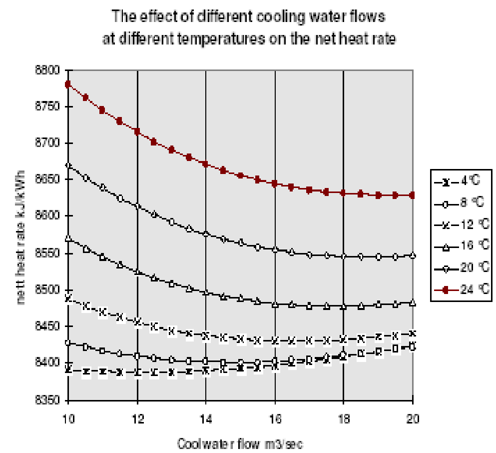

Fig. 3 Net heat rate as a function of cooling water flow and temperature

Cost savings

As an example the cost savings have been quantified for the 500 MWe operating point. Savings have been calculated for a 24 hour period, using fuel costs of EURO 1, 70/GJ. The result of a number of calculations is shown in figure 4. From this figure, it can be read how much the savings at different cooling water temperatures are, compared to the operation with maximum cooling water flow rate (20 m^3/s).

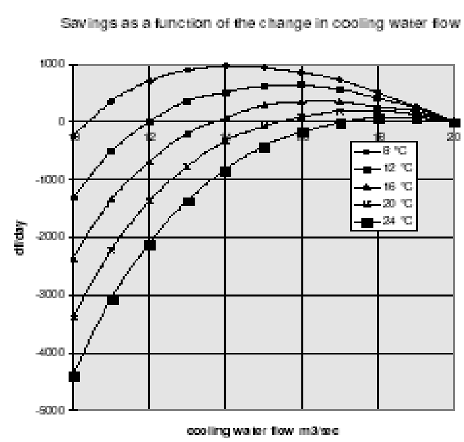

Fig. 4 Savings potential at production level of 500MWe

Conclusion:

1. The combined heat transfer and thermodynamics analysis and simple modeling offers a compact and fundamental explanation and importance for using these various techniques.
2. The optimum solution is found out with the approach of maximizing power and efficiency by applying different constraints. The approach is highlighted in

a new treatise and graduate level text on modern engineering thermodynamics.

3. Plant performance models are an invaluable tool for financial power plant optimization, in a changing, liberalizing energy market. This applies for all kinds of plants ranging from industrial cogeneration plants to coal fired power plant.
4. In a power plant a change in the cooling water flow rate, cooling the condenser of a power plant causes changes in condenser pressure and exhaust losses of the steam turbine and has a significant impact on plant performance.
5. In order to optimize the power plant, there should be optimum balance between cooling water temperature and mass flow rate, as it is also clear from the graph.

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