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Semi-Empirical Computational Tool for Design of Air-Cooled Condensers

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Many economic and environmental restrictions have resulted in the increase of use of dry cooling technology. An effort to minimize the consumption of water is one of main reasons why researchers and engineers are working on technologies for dry cooling which does not use water. Production of electricity in power plants is an important industrial activity where the wet cooling process is commonly utilized by means of cooling towers with a huge consumption of water which is evaporated into the atmosphere. An alternative technology for the withdrawal of the waste heat is the use of air-cooled condensers. Such condensers use the fan-forced air for water steam condensation and waste heat removal to the ambient environment. Apparently, the overall efficiency of the power plant is influenced by the design and performance characteristics of the air-cooled condenser. A proper setup and layout of the air-cooled condenser is therefore an important issue in the design and/or in the retrofits of power plants utilizing dry cooling systems and air-cooled condensers. A CFD analysis is a computational approach that is commonly utilized for the thermal analysis of the air-cooled condensers. However, CFD models and simulations are computationally demanding and often tricky. In the paper, the semi-empirical computational tool applicable for design and thermal investigations of air-cooled condensers is presented. The model is fast enough to complete simulations of operation of air-cooled condensers within dozens of minutes. The tool represents a unique combination of a simple numerical control-volume-based model of the air-cooled condenser which is coupled with empirical relationships gained from the literature. A good agreement between the semi-empirical model, data sheet parameters provided by producers of air-cooled condensers and experimentally gained data was achieved.

1. Introduction

Due to changes of environmental laws, many power plants are being forced to retrofit their facilities for power generation. The minimization of the water consumption is one of the main aims of such retrofits. The use of the once-through cooling water from rivers or oceans is therefore reduced and replaced by closed-circuit cooling water systems or by dry cooling systems. Bustamante et al. (2016) emphasized the need to preserve resources of fresh water for residential use and agriculture, and they also noted that power plants currently represent a big consumer of water. The authors reported that power plants account for about 40 % of fresh water withdrawals in the U.S. On the other hand, a dry cooling system exploits the air-cooled condenser which utilizes the fan-forced air for cooling and condensation of the water steam and its transformation to the saturated liquid. The currently used design for dry cooling in thermo-electric power plants is the A-frame layout of the air-cooled condenser. The design and performance of the air-cooled condenser directly influence the efficiency and operation of the power generation system. The optimal design of the air-cooled condenser is therefore a crucial task in the design and/or retrofits of power plants with dry cooling systems.
A CFD analysis is one of possible options how to computationally investigate the air-cooled condenser. However, such CFD solutions are usually very complicated and computationally extremely demanding. This is caused mainly due to a number of phenomena involved in the air-cooled condenser: multiphase fluid flow, heat transfer with the phase change, the presence of non-condensing gases and others. Kumar et al. (2014) carried out a 3D CFD transient analysis of the air-cooled condensed with the aim to investigate the process of the

natural convection. It was reported that the averaged Nusselt number increased by 20 % in comparison to results gained with the use of 2D model. The authors performed a comparison of their results with computational as well as experimental results of other authors and a good agreement was achieved. Chen et al. (2016) proposed a novel layout for the air-cooled condensers to improve the thermo-flow performance under ambient winds. The modification of the layout included in particular a novel vertical arrangement of the condenser. The study presented the use of the CFD simulations combined with experimental investigations. The results showed that a proposed layout allows for the increased mass flow rate of air through the condenser in both the absence and presence of winds. He et al. (2013) also investigated the performance of air-cooled condensers under various wind conditions by means of CFD with the use of user defined functions. It was found that the wind velocity and its direction significantly influence the operation of the condenser as they have a great impact on the pressure distribution around the platform with the condenser. O'Donovan and Grimes (2014) presented an effectiveness-NTU model of the air-cooled condenser which was employed for the prediction of condenser operation. The authors showed that neglecting steam side phenomena lead to significant differences between computational and experimental results. Further, the model was used to investigate a 50 MW hypothetical power plant with the installed air-cooled condenser. It was observed that beyond approximately 500 rpm of the fan the net plant output reduces and thus the optimum operating point exists. The authors reported that their model slightly over-predicted the net plant output determined experimentally. Kekaula et al. (2017) carried out a numerical study into the condensation process of water steam in the air-cooled condenser. The authors created a model in ANSYS Fluent and they used it for the analysis of heat transfer and fluid flow inside and outside of tubes of the condenser. A case study describing an influence of various parameters of the condenser to its performance was performed. Owen and Kröger (2017) presented a numerical investigation of the steam flow in the air-cooled condenser. They employed the combination of the CFD with numerical and analytical methods. The authors identified the inlet loss coefficient through the heat exchanger bundles and they reported that the steam flow can be significantly influenced by the inlet loss coefficient to the extent that steam flow does not have to conform to the expected pattern. The mentioned papers show that most studies employ CFD modelling for the investigation of the performance and behaviour of the air-cooled condensers. However, such models are rather complicated with a mesh usually having a vast number of elements due to large physical dimensions of the air-cooled condensers as well as due to physics modelled. Moreover, most studies do not discuss the complexity and computational requirements of models with no detailed information on how much computational time is needed and what powerful computers or clusters are applied. From the literature review, it is concluded that CFD analysis is a dominant tool for investigation of air-cooled condensers. However, CFD is not a practical tool when the condenser is designed because of its computational time and cost; it is rather applicable for a more detailed analysis where higher computational costs are justifiable.
In this paper, the semi-empirical computational tool for the design and thermal investigations of the air-cooled condensers is presented. The concept of the presented model is different from those CFD-based mentioned above. The model represents a combination of a numerical control-volume-based model of the air-cooled condenser which is coupled with empirical relationships. A number of empirical relationships for the solution of various physical phenomena were collected in a comprehensive literature review. The model operates in architecture with nested loops and the model iterates until a balance between various quantities is reached. This concept of the model allows for relatively fast simulations lasting minutes or dozens of minutes. The computational results gained with the model were compared to data provided by the manufacturers of the condensers as well as with experimentally gained data and a very good agreement was achieved. The presented model therefore represents a fast and simple alternative tool to CFD which allows for accurate design of air-cooled condensers.

2. Semi-empirical model of air-cooled condensers

2.1 Concept of the model

The presented model is devised for modelling of air-cooled condensers with the A-frame layout as shown in Figure 1. The model numerically solves heat transfer inside and outside the tubes (tube bundle) of the condenser, condensation of water steam inside the tubes and other phenomena described below. The model consists of three main sub-models discussed later. Phenomena in the tube bundle are solved by means of the 2D model – the tubes are partitioned into elements in the direction of the steam fluid flow. Each element accommodating steam with actual properties then interacts with neighbouring elements as well as with the air passing through the tube bundle. The model solves one module of the condenser which consists of two-half (left and right) tube bundle in the A-frame layout and one fan symmetrically forcing the air through the tube bundle. The tubes at their outer surface are equipped with fins for the enhancement of heat transfer. The user can specify numerous parameters related to the layout of the condenser including:

- Tubes: material, inner/outer diameter, length, thermal properties, layout of tubes (inline/staggered), number of tubes
- Fins: material, dimensions, distance, fouling factor
- Fan: dimensions, pressure-flow rate and power-flow rate characteristics
- Module: dimensions
- Ductwork of steam to the condenser: length, dimensions, local losses, pressure losses
- Steam entering the condenser: pressure, enthalpy, inlet concentration of air

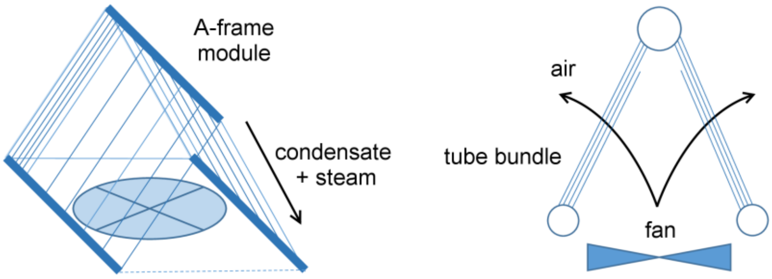

Figure 1: Schematic of the A-framed module of the air-cooled condenser

2.2 Sub-model for condensation and steam-related phenomena inside tubes

As mentioned above, the tube bundle is considered as a 2D system of nodes; each tube is partitioned into elements for which a set of balance equations is established. This means that the behaviour and parameters of the steam inside each element are generally different from those in other elements. The mass flow rate $\Delta\dot{m}_{steam}$ of the condensed steam in an element is determined from the heat balance of the element as

$$\Delta\dot{m}_{steam} = \frac{\dot{q}_{tube} L}{\Delta h} \tag{1}$$

where $\dot{q}_{tube}$ is the heat flux transferred per 1 m of the tube, L is the length of the element of the tube, and Δh is the difference between the enthalpies at the steam inlet and of the saturated liquid (water) corresponding to the pressure in the element. The heat flux $\dot{q}_{tube}$ is determined as

$$\dot{q}_{tube} = k \frac{\pi D_0}{4} \Delta T_{log} \tag{2}$$

where k is the overall heat transfer coefficient, D_0 is the inner diameter of the tubes, and ΔT_{log} is the logarithmic mean temperature difference between the air temperature outside the tube and the temperature of the saturated steam corresponding to the pressure in the element. The pressure drop in each element can be expressed as

$$\Delta p = \lambda_{gl} \rho_g \frac{w_{gl}^2}{2d_{free}} L \tag{3}$$

where λ_{gl} is the friction coefficient on the surface of the liquid film (condensed steam), ρ_g is the density of steam, w_{gl} is the velocity of steam inside the element of the tube, and d_{free} is the free diameter of the tube corresponding to the free cross-section of the tube (subtracting the liquid film of the condensed steam). The overall heat transfer coefficient k accounts for the heat transfer coefficients inside and outside the tubes and additional thermal resistances e.g. due to fin fouling, roughness of the inside surface of the tubes etc. As for the heat transfer coefficients, several empirical relationships were collected in the literature review. The model allows considering following phenomena related to the interior steam side of the tubes (in each element):

- Determination of the steam-tube heat transfer coefficient
- Determination of the pressure drop and the partial pressure of steam influencing the condensation
- Reduction of the cross-section area of the tube due to the creation of the liquid film of the condensed steam
- Determination of the mass flow rate of air mixed to the steam which influences the partial pressure of steam and condensation through the reduced steam-tube heat transfer coefficient
- Correction of the steam-tube heat transfer coefficient according to the steam velocity inside the tubes
- Correction of the steam-tube heat transfer coefficient according to the content of air in the steam (non-condensing gases mixed to the steam)

- Check against the overflow (glut) of tubes due to the condensed steam (its high velocity)

2.3 Sub-model for air-related phenomena outside tubes

The sub-model for heat transfer outside the tubes particularly solves the heat transfer from the tubes through the fins to the ambient air which is forced by the fan through the tube bundle. The heat transfer coefficient on the surface of the fins is determined from empirical relationships for the Nusselt number. The Reynolds number for the finned tubes is first determined for the tube without the fins and a correction taking into account the heat transfer enhancement due to fins is consequently carried out. By default, the air flow through the tube bundle is assumed uniform but the user can specify the distribution along the tubes. The sub-model for the air-related phenomena allows for:

- Determination of tube/fin-air heat transfer coefficient outside the tubes
- Correction according to the layout of the tubes (inline/staggered)
- Correction of the air velocity according to the configuration of fins and to the temperature of air
- Determination of the effectiveness of fins
- Determination of thermal resistance between the tube and the fins

In the operation of the air-cooled condenser, the temperature of air forced by the fan through the tube bundle increases as it receives heat from the condensing steam inside the tubes. The temperature increase of air is determined in each element of the 2D model of the tube bundle according to

$$t_{air,out} = t_{air,in} + \frac{\dot{q}_{tube}}{c_p\, w_0\, \rho_{air}\, s_{tubes}} \tag{4}$$

where $t_{air,out}$ and $t_{air,in}$ are the temperatures behind (outlet) and before (inlet) the element of the tube, c_p is the specific heat of air at constant pressure, w_0 is the free stream velocity of air, ρ_{air} is the temperature-dependent density of air, and s_{tubes} is the axial distance between the tubes positioned in one row.

2.4 Sub-model for fan

The third sub-model is devised for the solution of phenomena related to the fan and to the air flowing through the tube bundle. A particular type of the fan and its blade angle are specified by the definition of two quadratic relationships from the datasheet provided by the manufacturer of the fan: the dependence of the static pressure on the flow rate of air, and the dependence of the fan shaft power on the flow rate of air. The sub-model is iteratively evaluated and allows for:

- Determination of the working point of the fan
- Determination of the pressure drop of the tube bundle due to the air flow through it
- Determination of the required pressure increase in the fan
- Determination of the power consumption of the fan

2.5 Functionality of the model for air-cooled condensers

The presented model has three main functions which allow for:

- Design computation of the air-cooled condenser
- Verification computation of the air-cooled condenser
- Creation of diagrams with vacuum curves

All the functions call iteratively the model in a loop. The functions also require the definition of the layout (geometry) and other parameters of the module. The design computation serves as a tool for designing and dimensioning of the air-cooled condenser. The user defines the mass flow rate of steam to be condensated, its enthalpy and pressure at the outlet of the turbine. The model runs the calculation which results in the number of modules (with one fan per module) needed to condensate the defined mass flow rate of steam. The pressure of the steam is slightly corrected (reduced) to fulfil requirements to the mass flow rate of steam and the number of modules. The verification calculation reads the following data from the user: the mass flow rate of steam to be condensated, the number of modules, and the enthalpy of the steam at the outlet of the turbine. The verification calculation then determines the pressure of steam which is needed at the outlet of the turbine. Finally, the function designed for the creation of diagrams with vacuum curves iteratively runs the model and draws the so-called vacuum curves. Such curves characterize the thermal behaviour of the condenser under various conditions. Two types of the vacuum curves are drawn by the model: (a) dependence of the steam pressure on the mass flow rate of the steam for various temperatures of the ambient air, and (b) dependence of the steam pressure on the ambient air temperatures for various mass flow rates of the steam. Figure 2 shows an example of both the types of the vacuum curves created with the use of the model.

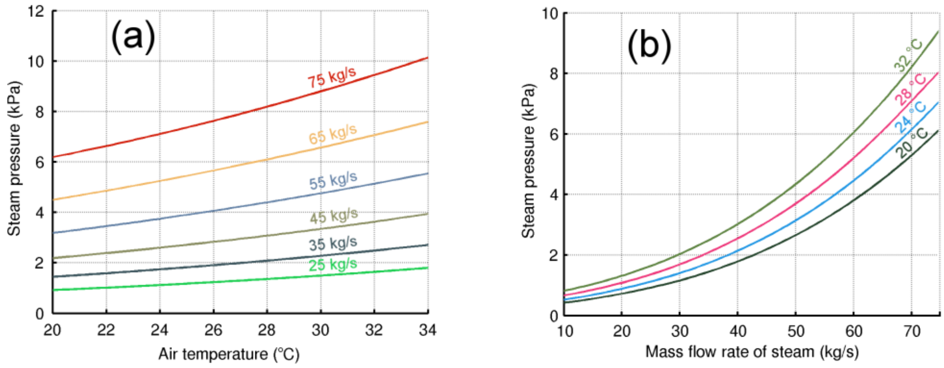

Figure 2: Plots with vacuum curves created with the use of the model for an air-cooled condenser (a) air temperature (b) mass flow rate of steam

2.6 Coding and software implementation

The model was implemented as a standard computer application suitable for the use by engineers and designers of air-cooled condensers. The application consists of two parts: the computational core and the graphics user interface. Both the part was created in the .NET framework and coded in the C# programming language. The use of the .NET framework has a benefit in practical applications: any architecture (PC, tablet, phone) with the installed .NET can run the program. Figure 3 shows a screenshot of the application.

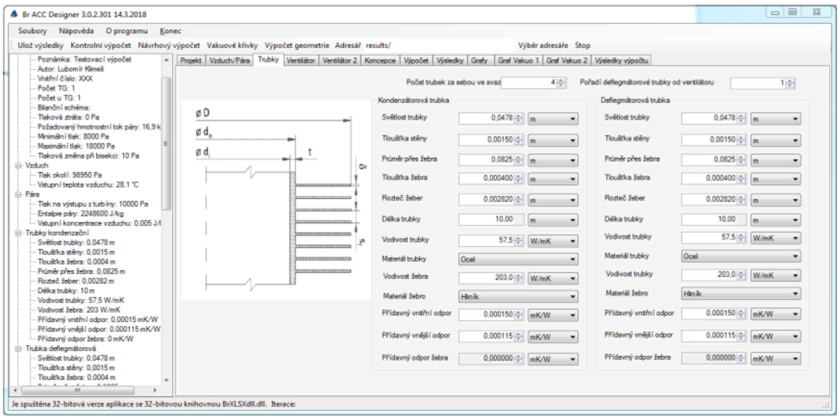

Figure 3: Screenshot of the application with the semi-empirical model of air-cooled condensers. Screenshot shows a tab with the setting of the tube bundle (labels are in Czech)

3. Comparison of the model with data provided by manufacturers of air-cooled condensers

The functionality of the presented semi-empirical model of air-cooled condensers was verified by means of (a) the comparison of computational results with datasheet parameters provided by manufacturers of air-cooled condensers and by means of (b) the experimentally determined data which were collected during the measurements of the air-cooled condenser operation. This air-cooled condenser is a part of the waste incinerator installed at the SAKO Company located in Brno, Czech Republic, having facilities for heat recovery and for waste-to-energy technology. In this paper, only the comparison of the model with datasheet parameters – case (a) – is presented.

Four air-cooled condensers and their datasheet parameters were considered in the comparison. The heat power of the condensers ranges between 27 MW and 200 MW and they include from 4 modules up to 30 modules. The main inputs used for the configuration of the model are presented in Table 1. Table 2 then contains the results computed with the use of the model. The number of modules required for the fulfilment of the operational parameters was considered as the main parameter in the comparison as it is presented in the datasheets of the condenser and guaranteed by their manufacturers. Other output parameters shown in Table 2 represent quantities which usually need to be measured directly during the operation of the actual condenser and those are not presented in the paper.

Table 1: Inputs to the semi-empirical model of the air-cooled condenser

Input parameter	Condenser 1	Condenser 2	Condenser 3	Condenser 4
Enthalpy of steam [kJ/kg]	2,220	2,302	2,192	2,394
Ambient air temperature [°C]	26	28	18	25
Inlet steam pressure [Pa]	6,000	12,000	8,500	6,500
Air flow rate through tube bundle [m^3/h]	825	640	710	940

As mentioned, Table 2 shows the numbers of modules needed to operate the condensers in designed operation. Two numbers are compared to each other: calculated by the model and gained from datasheets provided by manufacturers. As can be seen in Table 2, a very good agreement was achieved. In case of smaller condensers (Condenser 1 and 2), the model slightly over-predicts the number of modules by one module. In case of Condenser 3 and 4 the model predicts the identical number of modules as the manufacturers claim in their datasheets. All the calculations (for each of Condenser 1–4) were performed in less than 20 minutes (the elapsed real time). These results demonstrate that the presented semi-empirical model is a tool suitable for accurate and fast investigation of thermal behaviour of air-cooled condensers.

Table 2: Outputs of the model and the comparison with datasheet parameters of the air-cooled condensers

Output parameter	Condenser 1	Condenser 2	Condenser 3	Condenser 4
Pressure increase required by fan [Pa]	110	110	113	124
Heat power of one module [MW]	5.4	9.2	11.8	8.1
Mass rate of steam per module [kg/s]	9.36	15.84	20.88	12.96
Number of modules (model)	6	5	12	25
Number of modules (datasheets)	5	4	12	25
Total heat power (model) [MW]	32.4	46.0	141.6	202.5

4. Conclusions

The paper presents the development and testing of the semi-empirical computational tool for thermal simulations of air-cooled condensers. The model is based on a 2D model of the tube bundle and it contains a number of empirical relationships accounting for various phenomena related both to the steam and to the air flowing through the tube bundle. These also include more complicated phenomena such as the formation of liquid film in the tubes, presence of non-condensing gases (air) in the steam influencing the partial pressure of steam and its condensation, as well as pressure drops of the finned tube bundle and the operational point of the fan. In comparison to CFD simulations, the model is fast and its accordance with parameters from datasheets provided by manufacturers of air-cooled condensers demonstrates a good accuracy of the model.

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References

Bustamante J.G., Rattner A.S., Garimella S., 2016, Achieving Near-Water-Cooled Power Plant Performance with Air-Cooled Condensers, Applied Thermal Engineering, 105, 362-371.

Chen L., Yang L., Du X., Yang Y., 2016, A Novel Layout of Air-Cooled Condensers to Improve Thermo-Flow Performances, Applied Energy, 165, 244-259.

He W.F., Dai Y.P., Wang J.F., Li M.Q., Ma Q.Z., 2013, Performance Prediction of an Air-Cooled Condenser Using UDF Method, Applied Thermal Engineering, 50, 1339-1350.

Kekaula K., Chen Y., Ma T., Wang Q.-W., 2017, Numerical Investigation of Condensation in Inclined Tube Air-Cooled Condensers, Applied Thermal Engineering, 118, 418-429.

Kumar A., Joshi J.B., Nayak A.K., Vijayan P.K., 2014, 3D CFD Simulation of Air Cooled Condenser-I: Natural Convection over a Circular Cylinder, International Journal of Heat and Mass Transfer, 78, 1265-1238.

O'Donovan A., Grimes R., 2014, A Theoretical and Experimental Investigation into the Thermodynamic Performance of a 50 MW Power Plant with a Novel Modular Air-Cooled Condenser, Applied Thermal Engineering, 71, 119-129.

Owen M., Kröger D.G., 2017, A Numerical Investigation of Vapor Flow in Large Air-Cooled Condensers, Applied Thermal Engineering, 127, 157-164.