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Study of the effectiveness of the turbine condenser air extraction system using hydro ejectors

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Abstract

The aim of the paper is to investigate the effectiveness of the 18K380 steam turbine condenser air extraction system using hydro ejectors. Motivation for the analysis was a need of improvement of the energy conversion ratio of the power plant. To achieve this goal it was necessary to establish efficiency of each subsystem of the energy cycle. The air extraction system is not a highly power consuming system but it has great impact on the steam cycle efficiency by influence on the condensation temperature. The air extraction system effectiveness depends on a weather conditions, exactly on the ambient temperature, which raises the question whether it is worth to modernize the hydro ejectors or replace them by a centrifugal vacuum pumps. To establish the vacuum system effectiveness a new innovative mass flow measuring system has been implemented to measure an air-steam mixture flow and the fraction of the air mass in the mixture. The measuring system is based on a Venturi nozzle supplemented with a temperature drop during the mixture expansion.

Keywords: Condensation; Steam condenser; Venturi nozzle; Dalton's law; Partial pressure

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Nomenclature

$\dot{H}$	–	stream of enthalpy drop, kJ/s
$\dot{I}$	–	stream of enthalpy, kJ/s
$\dot{L}$	–	stream of work, kJ/s
$\dot{Q}$	–	stream of thermal energy, kJ/s
P	–	pressure, kPa
T	–	temperature, K
$\dot{l}$	–	stream of specific work
$\dot{m}$	–	mass stream, kg/s
s	–	specific entropy, kJ/(kg*K)
w	–	velocity, m/s
v	–	specific volume, m^3/kg
x	–	percent volume fraction of air in the air-steam mixture, %

Greek symbols

Δ	–	difference
η	–	efficiency
κ	–	adiabatic index

Subscripts

1	–	beginning of the process
2	–	end of the process
C	–	Carnot
t	–	technical work

1 Introduction

The PGE Belchatów Power Plant is the biggest thermal power plant in Europe and second largest fossil-fuel power station in the world. The power plant has twelve subcritical power units with capacity of electric power 370–390 MW and one supercritical energy block with a capacity of 858 MW. All units are supplied with lignite mined in the nearby opencast mine.

In twelve subcritical energy blocks for air removing from the main turbine and the turbo-pump condenser volume a hydro ejector pumping system is used. Although this system works flawlessly since the establishment of the power plant it is desire to improve the overall energy efficiency of the object. To attain this goal it is necessary to establish efficiency of all subsystems of the energy cycle, especially systems and devices which have direct influence on the facility overall energy conversion ratio. The air extraction system takes a special place in this approach, because it provides a vacuum in the condenser in latent way. Namely the condensation temperature, which according to the Carnot's efficiency is one of the power cycles most important parameters, is strongly correlated with the saturation pressure [1–3]

$$\eta_C = 1 - \frac{T_{min}}{T_{max}} \,, \tag{1}$$

where T_{min} and T_{max} are the cold and hot temperature reservoirs, respectively. If the low pressure part of the turbine and the condenser would be perfectly hermetic then the temperature-pressure set of condensation parameters would depends only on cooling water temperature. However high vacuum, which is usually in range of 5–10 kPa, causes some air leaks to the condenser volume. This air volume increases pressure in the condenser which decreases steam expansion in the turbine, therefore decreases its power [1,3,4]. If the pressure would be decreased by a vacuum pump in whole volume of the condenser evenly, so the proportion of the air-steam volume in the condenser would be constant, then the condensation phenomenon would takes place in a lower temperature than it would result from the saturation pressure, which is consistent with the Dalton's law and the partial pressure equation [2,3]. In real industrial installations, cooling water temperature depends on ambient temperature and is quite constant, thus, as a result of air in the condenser, the steam pressure is increasing. Moreover, when steam is condensing under partial pressure, water boiling temperature still depends on a total static pressure. This arises a temperature difference between the condensation and the saturation state, which is called subcooling. This phenomenon is particularly unwanted because 1 K subcooled of feeding water in amount of 240 kg/s causes increase of thermal power demand in boiler equal to 1 MW.

This short analysis shows that to provide proper operation of the steam turbine the steam condensation must takes place at possibly low temperature and pressure (saturation state parameters), which depend on cooling water temperature. To provide those optimal conditions it is necessary to eject the air from the condenser volume. This causes that though the air extraction system is not a highly power consuming one, and its proper operation has great impact on the steam cycle efficiency.

Moreover, in the current maintenance scenario, measurements of the condenser tightness is performed periodically by closing the valves on the suction line, which is subject to the relevant standards. The proportion of air-steam volume in the condenser could be determined online indirectly using pressure and temperature measurements in the condenser. However, those results are difficult to interpret, because fraction of the air in the condenser is uneven in volume, and parameters of the condensation strongly depends on the turbine load. Furthermore, in this case measurement of subcooling would be impossible due to small but very hot streams of steam and water coming from glands and auxiliary heaters.

To undertake a measurement of a mass flow of an air-steam mixture some analysis were already made in work of Kowalczyk *et al.* [5], using numerical tools as CFD (computational fluid dynamics) modeling [6,7]. There authors have proved that in case of high vacuum, for relatively small mass flow rate through the Venturi flow meter, the mass flow rate of the mixture can be estimated with quite good accuracy without the necessity of estimating a fraction of air and water in the mixture. Unfortunately, extra limitations additionally decrease the measuring range of the device, which is already very narrow for vacuum conditions. Moreover, a mass flow rate of air is unknown . Therefore in this paper a new method of estimating the air-steam mixture composition is presented.

2 Measuring system

Implemented measuring system was designed for physical conditions which rarely occurs in other industrial installations than steam condensers air extraction systems. Namely absolute pressure in range of 4–15 kPa, temperature equal to saturation conditions or slightly above, which gives 29–55 °C, mixture of air and saturated or wet steam. At the beginning of the project the fraction of air in the mixture was unknown. Mass flow rate of the mixture was roughly estimated using literature data [4,8].

The measuring system, called IMP-UPP-01, was installed in PGE Bełchatów Power Plant between the main condenser and the hydro ejecting pumps, which is presented on scheme in Fig. 1.
The mixture of air and steam is extracted from the condenser by hydro ejectors through a siphon in order to reduce the losses of a boiler water. Because the mixture is sucked form the condenser close above water line – where air concentration is the largest, but also steam dryness fraction is the lowest – the mixture can occur in pipeline – where the IMP-UPP-01 is installed – in three possible phases compositions: air-superheated steam, air-saturated steam or air-wet steam.

Preliminary determination of physical condition of the measurement allowed to define a measurement method, which use large differences between thermodynamic parameters for air and steam around the saturation point. Those differences can be measure as a temperature drop during expansion in a nozzle. Air under low pressure and for small temperature drop under expansion process can be modeled using an ideal gas model with very good accuracy. In this case adiabatic process equation can be used to determine the temperature drop:

$$\Delta T = T_1 - T_2 = T_1 \left[1 - \left(\frac{P_1}{P_2} \right)^{\frac{\kappa}{\kappa-1}} \right] . \tag{2}$$

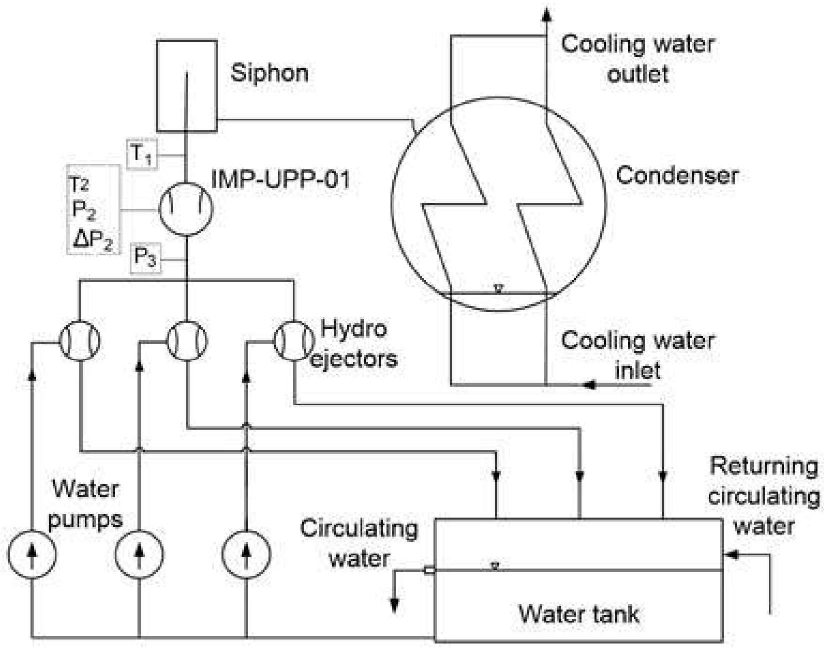

Figure 1: Scheme of measuring system using IMP-UPP-01 measuring device.

More problematic is calculation of temperature drop during fast expansion of steam in the nozzle. If the expansion occurs in range of superheated steam, the process can be described using ideal gas model. Because temperature drop is not larger than about 30 K, inaccuracy of ideal gas model is negligible. Furthermore, whole process runs under very low pressure. However, if the expansion ends in region of wet steam, ideal gas model assumptions are far from being achieved, moreover phenomenon of steam supercooling occurs. This process can be preliminary described using Zeuner-Rankine model [3]. More accuracy calculations needs more complicated real gas models, as well as calculations of air-steam mixture properties, where, e.g., Beattie-Bridgeman's real gas model can be applied [3].

Presented approach will be discussed on a simply model of ideal gas model for air and steam tables. For example, pressure drop on the Venturi nozzle used in the system equal to 700 Pa, at pressure in the pipeline equal to 6.2 kPa and temperature 36.6 °C, gives temperature drop for steam equal to about 2.1 K and for air about 10.3 K. By including of molar mass and thermodynamic parameters of steam and air under those thermodynamic conditions, using numerical methods it is possible to balance the enthalpy of the mixture and establish precise fraction of steam and air according to the first law of thermodynamics

$$\dot{Q} = \dot{I}_1 - \dot{I}_2 - \dot{m}\frac{w_1^2 - w_2^2}{2} + \dot{L}_t \ . \tag{3}$$

The expansion process in the nozzle is assumed as an adiabatic ($\dot{Q} = 0$), which gives

$$\dot{H} \ = \dot{I}_1 - \dot{I}_2 = \dot{m}\left(\frac{w_1^2 - w_2^2}{2} - \dot{l}_t\right) \ , \tag{4}$$

where stream of specific technical work, $\dot{l}_t$, is defined as

$$\dot{l}_t = -\int_1^2 v \ dP \ . \tag{5}$$

Specific volume can be determined using one of the gas models [2,3].

Enthalpy is an extensive parameter which makes it also and additiveone, so

$$\dot{H}_{\ mixture} = \dot{H}_{\ air} + \dot{H}_{\ steam} \ . \tag{6}$$

Using an adiabatic process equation for ideal gas for air, temperature after expansion by measuring pressure drop on the nozzle can be estimated. Measured pressure must be divided on the partial pressures for steam, P_{steam}, and air, P_{air},

$$T_{2\ air} = T_1 \left[1 - \left(\frac{P_{1\ air}}{P_{2\ air}}\right)^{\frac{\kappa\_air}{\kappa\_air-1}}\right] \ . \tag{7}$$

Steam temperature after expansion should be determinate using one of the real gas model with taking into account also subcooling phenomenon, however in preliminary analysis it can be estimated using steam tables for measured pressure and calculated specific entropy:

$$T_{2\ steam} = T(P_{2\ steam}, s_{1\ steam}) \ . \tag{8}$$

When total stream of enthalpy is finally calculated, Eg. (6), Eqs. 4 and 5 can be now solved using numerical methods to estimate composition of the mixture, for which difference between total stream of enthalpy calculated as a sum of air and steam enthalpy and enthalpy stream calculated for the mixture will be acceptable.

In Fig. 2 a diagram of temperature after the expansion in the Venturi nozzle, for parameters given above, for variable composition of the mixture, is presented. Dashed line with round markers represent the lowest temperature reached during

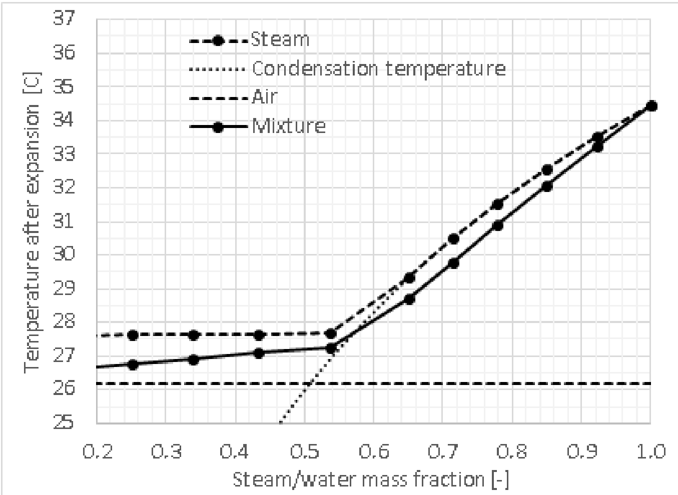

Figure 2: Temperature after the Venturi nozzle for variable composition of the mixture.

the expansion in the nozzle for steam under partial pressure, but without consideration of air fraction. Dashed line without markers represent temperature of air after expansion. This temperature is constant, the same as for steam under low partial pressure, because air is a gas (superheated steam) and its temperature drop depends on a relevant pressure drop value during the expansion. Solid line with round markers shows temperature after the expansion for different compositions of the mixture, taking into account partial pressures, influence of air and condensation phenomena. Additionally dotted line shows condensation temperature for partial pressure of steam for variable composition of the mixture (considered for partial pressures without influence of air). Above this line steam is superheated, on the line it is in a saturation state and below is a water. The mixture temperature can be lower than the saturation temperature only if some fraction of the steam in the mixture will condensate. This will decrease the volume fraction of steam, which is equivalent with steam partial pressure decrease, but sum of steam and water mass fraction in the mixture will be constant. Because water do not cause partial pressure, air partial pressure has to increase.

Presented procedure was validated on an industrial installation for conditions when mixture was composed of air and wet steam, which allowed to use Dalton's law. Validation in whole operation range was undertook using CFD modeling.

3 Analysis of the effectiveness of the air extraction system

The main aim of the steam condenser air extraction system is to hold possibly the lowest air concentration in the condenser volume. This minimize two phenomena which decrease heat exchange efficiency in the condenser. The first phenomenon concerns decrease of heat conductivity around the heat transfer surfaces. Part of steam is condensing in volume but second part – on heat transfer surfaces. When steam is decreasing its volume (about 1000 times) during the condensation process this free volume is filled by steam and air unevenly, so during the process air concentration around the cooling surfaces is increasing. This decrease contact between steam and the cooling surfaces. Furthermore, air has low heat conductivity coefficient which additionally is worsening the heat transfer. The second phenomenon is related to the partial pressure law, which was discussed in the introduction.

To extract air from the condenser, a suction force driven by pressure lower than pressure in the condenser is needed. This can be realized by rotary pump, steam ejectors or hydro ejectors. Each of those devices has advantages and disadvantages. Hydro ejectors which are used in the Bełchatów Power Plant are driven by water pumps, but in opposite to the steam ejectors or rotary pumps, the main suction force is not caused by momentum exchange but by the volume change of condensing steam. It means that to achieve suction force water driving the ejectors must be under lower temperature than condensing steam. Like for others pumps also for ejector the highest suction force will occur for blocked flow, and it will be equal to saturation pressure for driving water temperature.

Air concentration in the condenser is not even so by proper arrangement of suction pipes it is possible to extract mixture relatively reach in air. Air concentration in suction pipeline in most often about 5 times greater than in condenser volume. However, part of sucked steam is condensing in the ejectors, which is heating the driving water. The water is pumped from a water tank installed in the machine hall. Because water in the tank is exchanging heat with the environmental too slow to provide proper temperature difference between driving water and sucked mixture, water is circulating with external open reservoir of water. Water temperature in the external reservoir depends on the atmospheric conditions.

During the data analyzing process an important parameter has been established, which relates cause with an effect. Namely air concentration in the condenser was linked with a driving force of ejectors expressed as a driving water temperature. To minimalize influence of pressure in the condenser (which have great impact on the air leaking phenomena) gathered data were divided in few groups of pressure. During the air extraction process, water pumps (driving the hydro ejectors) power was constant. Results are presented in Figs. 3–7.

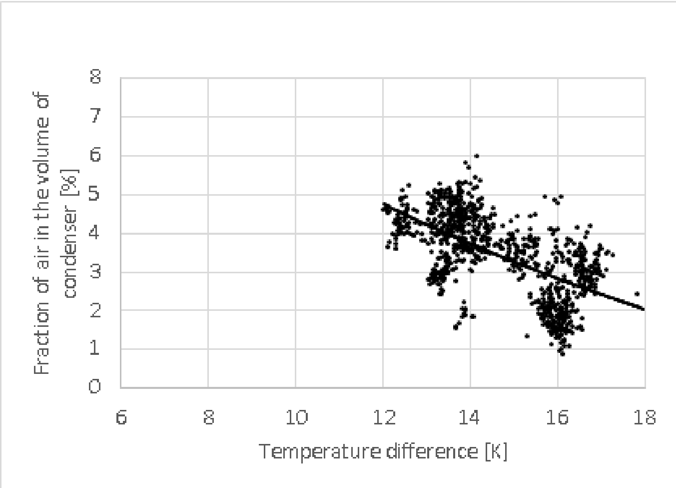

Figure 3: Fraction of air in the condenser volume vs. temperature difference between condensing steam and water driving hydro ejectors for absolute pressure in the condenser in range of 8–9 kPa.

For higher pressures occurs higher temperature difference, which is correlated with difference between ambient temperature (water driving hydro ejectors temperature) and condensation temperature in the condenser. In each case, beside the lowest pressure 4–5 kPa, there is a correlation between air concentration in the condenser and temperature of water driving the hydro ejectors. For the lowest pressure the correlation was not observed, because temperature difference was in narrow range (mainly 9 to 10 °C). Also small amount of control points was collected, because such low pressure is attained only for very low electric power generation (about 190 MW). Low pressure leads also to higher air leaks to the condenser and lower load of the condenser heat exchange surfaces, which has influence on the air distribution in the condenser volume. During pressure change in the condenser the mixture composition in the suction pipeline is changing from about 10/140 (kg/h of air to kg/h of steam) for 9 kPa to about 14/20 (kg/h of air to kg/h of steam) for 5 kPa.

The measuring system has also recorded some points with large deviation from the mean values. Those deviations can be caused by turbine power control

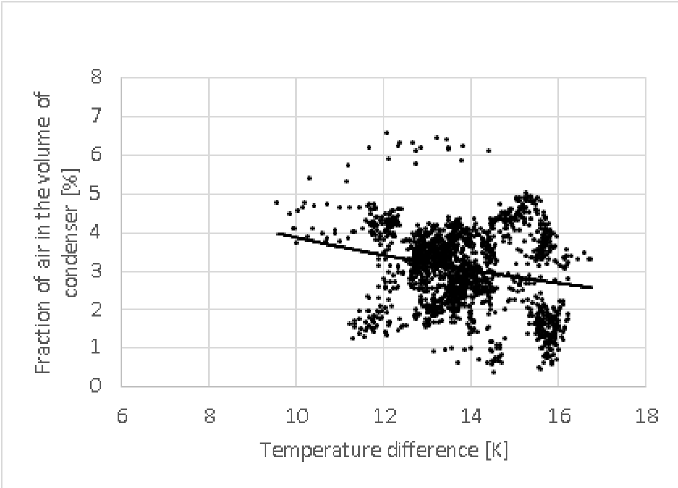

Figure 4: Fraction of air in the condenser volume vs. temperature difference between condensing steam and water driving hydro ejectors for absolute pressure in the condenser in range of 7–8 kPa.

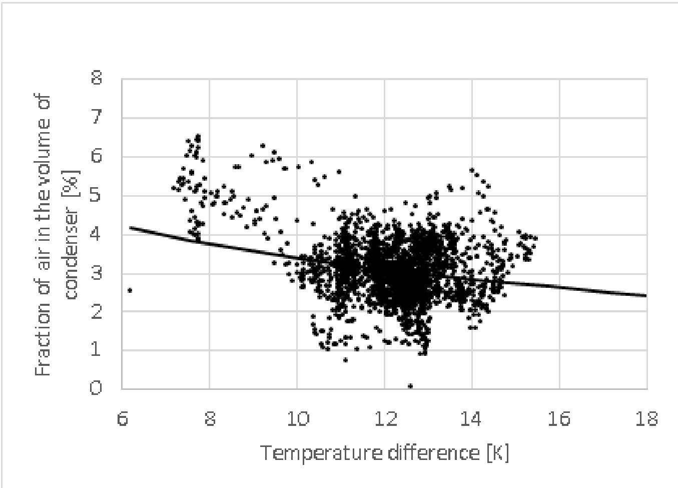

Figure 5: Fraction of air in the condenser volume vs. temperature difference between condensing steam and water driving hydro ejectors for absolute pressure in the condenser in range of 6–7 kPa.

processes (transient states), violent nature of the condensation phenomena and condensation of steam in impulse tubes, which connects the pressure sensors. Time constant of measuring system (calculating loop) is quite low – less than

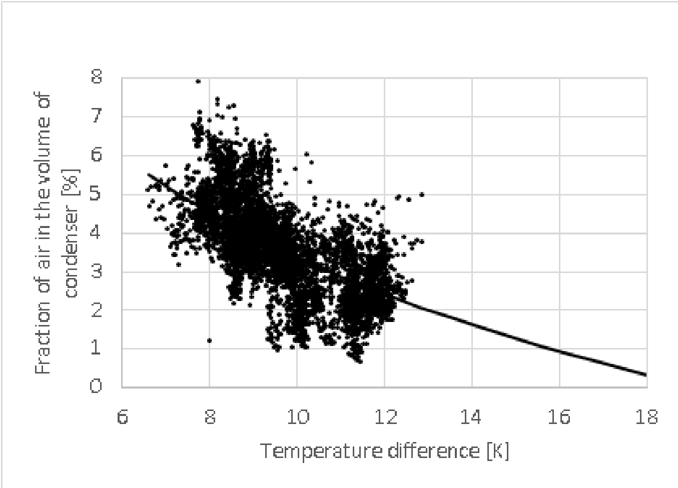

Figure 6: Fraction of air in the condenser volume vs. temperature difference between condensing steam and water driving hydro ejectors for absolute pressure in the condenser in range of 5–6 kPa.

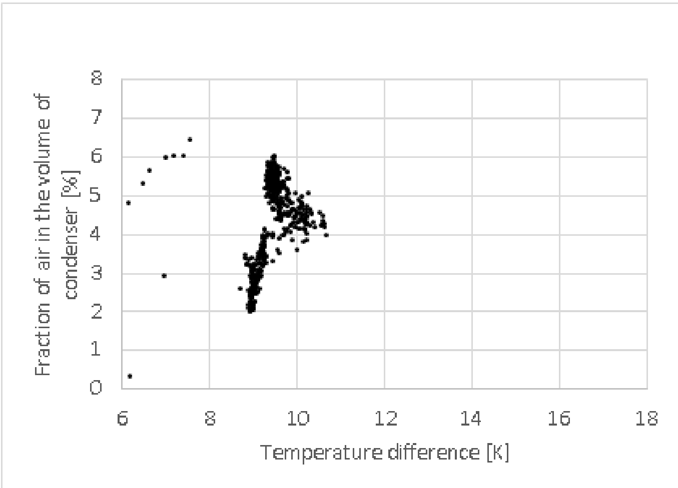

Figure 7: Fraction of air in the condenser volume vs. temperature difference between condensing steam and water driving hydro ejectors for absolute pressure in the condenser in range of 4–5 kPa.

450 ms. Particularly fast is pressure measurement, which takes only about 20 ms, therefore rapid pressure peaks may disturb the calculations.

4 Conclusions

Although measuring system was applied on the steam condenser air extraction installation about two month ago, and measurement data were gathered only for relatively low and quite constant atmospheric conditions, a certain regularity was noted. Namely decrease of temperature difference between condensing steam and water driving hydro ejectors leads to increase of air fraction in the condenser volume. This in turn leads to the condensate subcooling, which has negative influence on the energy conversion efficiency. Correlation between air fraction in the condenser and the condensate subcooling is described by linear function

$$\Delta T_{subcooling} = 0.1102x + 0.0135 \ , \tag{9}$$

where x refers to percent volume fraction of air in the air-steam mixture. The correlation is very strong, which confirms the coefficient of determination R^2 equal to 0.9989.

Air fraction in the condenser volume is a good effectiveness indicator, because it is directly linking suction force caused by the temperature difference (strongly correlated with the saturation pressure) with the effect: the air concentration in the condenser. To confirm the correctness of proposed correlation, more data must be gathered. Especially for variable atmospheric conditions. Moreover, an important aspect of undertaken research is usage of propose measurements in thermodynamic calculations of whole steam cycle. This kind of calculations can be performed using CFM (computational flow mechanics) codes, which gives opportunity to establish the influence of the modernization on the power plant efficiency [9–14].

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