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Integrated multiscale simulation of combined heat and power based district heating system

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ABSTRACT

Many studies have been carried out separately on combined heat and power and district heating. However, little work has been done considering the heat source, the district heating network and the heat users simultaneously, especially when it comes to the heating system with large-scale combined heat and power plant. For the purpose of energy conservation, it is very important to know well the system performance of the integrated heating system from the very primary fuel input to the terminal heat users. This paper set up a model of 300 MW electric power rated air-cooled combined heat and power plant using Ebsilon software, which was validated according to the design data from the turbine manufacturer. Then, the model of heating network and heat users were developed based on the fundamental theories of fluid mechanics and heat transfer. Finally the combined heat and power based district heating system was obtained and the system performances within multiscale scope of the system were analyzed using the developed Ebsilon model. Topics with regard to the heat loss, the pressure drop, the pump power consumption and the supply temperatures of the district heating network were discussed. Besides, the operational issues of the integrated system were also researched. Several useful conclusions were drawn. It was found that a lower design primary supply temperature of the district heating network would give a higher seasonal energy efficiency of the integrated system throughout the whole heating season. Moreover, it was not always right to relate low design supply temperatures to high pump power consumptions and high heat losses in the district heating network, since the results showed that the seasonal pump power consumption and the heat loss would decrease with a lower design primary supply temperature. Therefore, from the perspective of seasonal consideration, low temperature district heating has an even more bright future compared to just considering the design heat load condition. Both the combined heat and power plant and the low temperature district heating network were simulated in detail and integrated, including the part heat load conditions, which is one novelty of this article. The simulation in this paper could be considered as the basis for the further improvement and optimization of combined heat and power based district heating systems.

1. Introduction

Nearly every progress of science and technology made by mankind comes along with the excessive exploration of natural resources and serious pollutions. So many changes have been made to the nature on the earth that the fact of energy depletion and global warming is threatening us with, unfortunately, a grave future. One of the most promising ways to dismiss or release this bad situation is to make full use of the remaining energy resources, including renewable energy and fossil fuel, since it is unlikely to stop the development of science or to reduce the daily increasing energy demand of mankind society at present. In 2013, the global primary energy consumption increased by 2.3%, with a 1.8% acceleration over the year 2012 [1].

Combined heat and power (CHP) can be an energy efficient and environmentally friendly way for energy conversion and utilization, especially when it combines with the customary technology of combined cycle using natural gas [2,3]. Researches all over the world have been focused on the old but vital technology of CHP. To evaluate the energy conservation characteristics of CHP plants, a series of indicators have been proposed [4–8]. Meanwhile, to

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Nomenclature

Abbreviations
ACC air-cooled condenser
CCHP combined cooling heat and power
CHP combined heat and power
DH district heating
LPC low pressure cylinder

Greek symbols
η_{av} period energy efficiency, –
η_t energy efficiency, –
λ thermal conductivity, W/(m K)
λ_0 thermal conductivity of earth, W/(m K)
ρ density of water, kg/m^3
τ time, h
τ_0 duration of heating season, h

Latin symbols
$\dot{G}$ water flow rate in radiator, kg/s
$\dot{Q}$ heat rate/load, W
$\dot{Q}_i$ input energy of CHP plant, kW
$\dot{Q}_{los}$ rate of heat loss, W
$\dot{Q}_{max}$ maximum heat load, W
Δh water enthalpy drop in radiator, J/kg
ΔP pressure drop, Pa
$\Delta T_{m,r}$ radiator temperature difference, °C
a, b coefficient parameters of radiator
A_r heat transfer area of radiator, m^2
c_p specific heat at constant pressure, J/(kg K)
D_1 inner pipe diameter, m
D_2 outer diameter of pipe, m
D_3 outer diameter of insulation, m
f friction factor, –
h outer diameter of insulation, W/(m^2 K)
K roughness of inner pipe surface, m
k_r heat transfer coefficient of radiator, W/(m^2 K)
L length of pipe, m
P_e power output of CHP plant, kW
R specific frictional resistance, Pa/m
R_1 thermal resistance of insulated pipe, K/W
R_2 thermal resistance of soil over pipe casing, K/W
S shape factor of heat conduction, m
$T_{a,min}$ lowest calculated ambient temperature, °C
$T_{a,st}$ ambient temperature when heating season starts, °C
T_a ambient temperature, °C
$T_{i,p}$ inlet pipe temperature, °C
$T_{i,r}$ inlet temperature of radiator, °C
$T_{m,p}$ cross section mean temperature of water in pipe, °C
T_n indoor temperature needed, °C
$T_{o,p}$ outlet pipe temperature, °C
$T_{o,r}$ outlet temperature of radiator, °C
T_s surface temperature of the earth, °C
U heat transfer coefficient of insulated pipe, W/(m^2 K)
v velocity of water, m/s
z buried depth of pipe centerline, m

Subscripts
a ambient
c pipe casing
i inlet
m mean
max maximum
min minimum
n needed
o outlet
p pipe
r radiator
w water

bring up the efficiencies of CHP systems, a series of technical measures has been studied with respect to different system types and boundaries [9]. However, most of the recent published studies on CHP are mainly focused on natural gas based small-scale trigeneration systems, such as combined cooling, heat and power (CCHP) [10,11], combined renewable energy such as CHP with wind power or solar power [12,13]. Research on solely conventional CHP with large-scale coal-fired units is relatively insufficient, leading to the reality that the options and parameters of large-scale CHP systems have not been adjusted well with the increasing unit capacities, heat load scales and temperature levels. Besides, with the world-wide hot research and discussion of CO_2 reduction, fossil fuel is becoming not such popular as renewable energy. However, it is impossible to change totally to renewable energy instantly due to present primary energy reserves and infrastructures for countries like China, South Africa, India, Poland, etc. The coal-fired power plants will still be important within foreseeable future. Therefore, intensive study of large-scale coal-fired CHP systems is still an urgent need of top priority in face of current serious energy shortage and environmental degradation.

District heating (DH) is another hot topic in the residential sector, especially under the pressure of energy and environmental problems these years [14,15]. The fundamental idea of DH is expressed as: to use local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating, by using a heat distribution network of pipes as a local market place [16]. Gadd and Werner [17,18] researched on the heat load patterns shows that normal heat load patterns vary with applied control strategy, season and customer category. Persson and Werner [19,20] investigated the industrial excess heat utilization in DH and the competitiveness of future DH systems, and concluded that there is no direct barriers for the utilization of industrial excess heat for DH within EU27 and that reduced heat demands in high heat density areas will not be a general barrier for DH in the future. With the goal to decrease the primary return temperature of the heating network, studies have been carried out with respect to the optimization of substation control strategy which constitutes the interface between the DH network and the heat customers [21–23]. Recently, low temperature DH is becoming a popular research field due to more and more appropriated insulation and airtight building envelopes. Brand and Svendsen [24] studied a typical Danish single-family house connected to DH from the 1970s, the results show that a maximum supply temperature below 60 °C would be feasible for 98% of the year with a small refurbishment like changing the windows. Lund et al. [25] defined the concept of 4th generation DH and smart thermal grid. In their definition, low supply temperature, low grid losses and low temperature heat sources are three important features of the future 4th generation DH. Meanwhile, it was also pointed out that the supply temperature as low as 40 °C can be used for space heating systems. However, there is a dearth of research related to the optimal low supply temperature of the primary heating network. Besides, all these DH related researches are heating network or heat load and building related studies. Few studies have combined