Energy 86 (2015) 589–602

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Key issues and solutions in a district heating system using low-grade industrial waste heat

Hao Fang, Jianjun Xia*, Yi Jiang

Building Energy Research Center, School of Architecture, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 22 September 2014
Received in revised form
3 April 2015
Accepted 15 April 2015
Available online 16 May 2015

Keywords:
Low-grade industrial waste heat
Low-temperature district heating
Multiple-grade waste heat collection
Long-distance delivery
Peak-shaving method
Tangency technology

ABSTRACT

Industrial waste heat is increasingly being recognized as an important source of heat for DH (district heating) systems in cold regions to fill shortfalls in heating requirements, while consuming less fossil energy than with conventional heating sources. Most existing cases of industrial waste heat utilization for heating merely focus on heat recovery from a single waste heat source for heating either in the factory in which the heat is generated or other buildings in the vicinity. The purpose of this paper is to discuss the key issues related to a DH system using two or more kinds of low-grade industrial waste heat, at a temperature between 20 °C and 90 °C, for users a long distance away from the heat sources, including the collection and integration of multiple-grade waste heat sources, long-distance delivery of waste heat, and peak shaving of the system. Solutions to these three issues are proposed to increase the efficiency of the system and for further and better promotion of such a system: 1) "Tangency technology" is designed and applied to find the optimal method of collecting heat from multiple waste heat sources. 2) Lowering the temperature of the return water on the primary side has been proven to be crucial to the collection and long-distance delivery of industrial waste heat. 3) Systems integrating both industrial waste heat and fossil-fuel heat are depicted. Industrial waste heat always provides the base load for the DH system, while the fossil-fuel heat acts as the peak shaver. Lastly, a case study undertaken in Chifeng in northern China demonstrates how these solutions act in a first-ever DH demonstration project using multiple sources of waste heat from a copper smelter. In all, 390,000 GJ of waste heat was recovered, 35,000 t of CO_2 emission was reduced, and over 150,000 t of water was saved.

1. Introduction

Energy efficiency is given a rather low priority in the field of manufacturing, especially in the energy-intensive industrial sectors, such as the manufacture of non-metallic mineral products and smelting of ferrous and non-ferrous metals. Large quantities of waste heat, mostly low grade between 30 °C and 100 °C [1–4], are discharged into the atmosphere during the production processes. In the United States, for example, 20–50% of the energy consumed by metal and non-metallic mineral manufacturing is lost as waste heat [5]. In Turkey, a cement plant was studied and the researcher asserted that 51% of the heat used in the process had been wasted [6]. In China, the largest industrial country in the world, it is believed that at least 50% of all energy used in industry is wasted, mostly in form of low-grade waste heat [7]. Using macro data, it has been estimated that a coal equivalent of nearly 260 million tons (tce), or 7.6 million TJ, of low-grade waste heat is lost in northern China each year [8].

As concerns about the global energy crisis and global warming have increased, it is becoming apparent that industrial waste heat should be recovered and reused. As a result, many projects addressing industrial waste heat recovery for heating have been set up worldwide. For instance, many trials were conducted in Europe in the 1980s: With government funding, several DH (district heating) networks using industrial waste heat were established in Sweden [9]; industrial waste heat from a steel mill was reported as being used for DH in Germany [10]; 2.4 MW of waste heat from a cement plant was being reused by a local DH system in Switzerland [11]; an electrically driven heat pump was applied to upgrade the industrial waste heat from 40 °C to 60 °C for DH in the Netherlands [1]. In China, similar attempts were undertaken after 2000, based on the existing literature and reports, with most such studies addressing the recovery of heat from the slag flushing water used in steel mills: Jigang and Xuangang took use of part of the waste heat

* Corresponding author. Tel.: +86 10 62775553; fax: +86 10 62770544.
E-mail address: xiajianjun@tsinghua.edu.cn (J. Xia).

http://dx.doi.org/10.1016/j.energy.2015.04.052
0360-5442/

from the slag flushing water for heating the staff dormitory with an area of 130,000 m^2 and 300,000 m^2, respectively [12,13]; Neiqiu County in Hebei Province planned to reuse waste heat from its local steel mill for heating over 2 million m^{2}of residential buildings [14].

To sum up, previous research has mainly focused on: 1) high-grade waste heat, e.g. steam, being directly reused for the production processes and hot-water provision within the factory where the heat is generated; 2) low-grade waste heat at a relatively high temperature (60–95 °C), e.g. slag flushing water in steel mills, recovered by specific heat exchangers for providing heating for the factory itself or buildings in the vicinity; 3) low-grade waste heat of a relatively low temperature (30–60 °C), e.g. circulating cooling water, recovered and upgraded by heat pumps for heating the factory itself or buildings in the vicinity.

However, these industrial waste heat based heating systems have inherent shortfalls or deficiencies: 1) the scale of the heating area is often insufficient, usually being no more than a small district, and therefore the heat demand does not rise enough to match the waste heat available from the factory, resulting in an insufficient recovery ratio; 2) the waste heat recovery process is simple, with only a single waste heat source being considered, or several waste heat sources in parallel which are then combined; 3) waste heat is mostly reused by the factory itself or in buildings in the vicinity, with very little long-distance delivery; 3) for low-temperature waste heat, only the application of heat pumps inside the factory has been proposed, with little consideration having been given to the integration of the heat sources, heating network, and terminals.

The purpose of this paper is to discuss the key issues related to low-grade industrial waste heat based DH systems, from the collection and delivery of waste heat to the regulation of the overall system. Corresponding solutions to these key issues will be proposed. Finally, a case study will be described to shed light on the importance of these issues and to demonstrate the solutions in an actual project.

2. Key issues and solutions in a DH system using low grade industrial waste heat

A low-grade industrial waste heat based DH system is essentially a DH system which consists of a heat source, heat sink/user, and heating network. The basic and main heat sources of this novel system are the low-grade industrial waste heat that is generated by manufacturing processes. In a factory where high-grade waste heat has already been reused, waste heat of less than 200 °C is still discarded into the atmosphere mostly by the evaporation of water in cooling towers and by forced air cooling. Generally speaking, in every factory, there are many unexploited low-grade waste heat sources. The low-grade waste heat is normally unstable and fluctuates with the production level. These outstanding features distinguish low-grade industrial waste heat based DH systems from conventional fossil-fueled systems, e.g. CHP (combined heat and power) plants and water boilers.

Therefore, some basic key technical issues should be solved before this system can be popularized, including: 1) the collection and integration of multiple-grade waste heat sources; 2) the long-distance delivery of waste heat; 3) peak shaving of the system, as shown in Fig. 1.

2.1. Collection and integration of multiple-grade waste heat sources

According to the type and grade of the heat source, the overwhelming majority of industrial waste heat can be categorized into: (1) high-temperature flue gas waste heat, e.g. flue gas from the exhausts of cyclones in cement plants; (2) high-temperature steam waste heat, e.g. steam from waste heat boilers in ferrous smelting factories; (3) high-temperature slag or residue waste heat, e.g. slag from the blast furnaces in iron works; (4) high-or medium-temperature product waste heat, e.g. steel slabs from casting workshops in steel mills and strong sulfuric acid in copper smelters; (5) low-temperature cooling medium waste heat, e.g. circulating cooling water in the walls of the blast furnaces of an iron works; (6) high-temperature combustible gas waste heat, e.g. the sensible and combustion heat of the blast furnace gas in an iron works; (7) low-temperature condensation water waste heat, e.g. condensation water from waste heat power generation turbines in ferrous and non-ferrous smelting factories.

It can be concluded that industrial waste heat sources are heterogeneous, and the distribution of the grades of heat is complicated. Most of the high-temperature waste heat, such as steam and combustible gas, has already been fully exploited within the factory, for the likes of power generation. Nevertheless, the low-grade industrial waste heat still has a wide range of grades, mostly between 30 °C and 200 °C. Figs. 2 and 3 illustrate the waste heat distribution in a copper smelter and an iron and steel works, respectively. These two figures are depicted as T-Q diagrams, in which the horizontal axis represents the rate of heat flow and the vertical axis represents the temperature. In a T-Q diagram, each line segment represents a single heat source. The length of the projection of a line segment along the horizontal axis indicates the quantity of waste heat, or to put it in another way, the rate of heat flow of each waste heat source equals to the value of the right endpoint minus that of the left endpoint in horizontal axis. The length of the projection along the vertical axis indicates the grade range of the corresponding waste heat. The left (right) endpoint is the temperature of the waste heat source after (before) cooling or heat dissipation.

Fig. 2 shows that all of the unexploited waste heat sources in the copper smelter are at temperatures of less than 200 °C, and over 85% of them are lower than 100 °C. Fig. 3 shows that more than half of the unexploited waste heat in the iron and steel works is low-grade waste heat at a temperature of less than 100 °C.

As the overall grade of industrial waste heat is low, extra high-grade heat sources are commonly necessary to satisfy the demand to supply water to the heating network. To avoid or at least lessen the consumption of extra high-grade heat sources, the optimal object is to raise the temperature of the supply water leaving the factory. Therefore, derived from the theories of thermodynamics and heat transfer, a methodology based on entransy theory is established.

Entransy is a physical quantity, derived from the analogy between heat and electricity, which provides a quantitative description of the heat transfer ability [15]. Experts and researchers studying entransy theory have asserted that entransy inevitably dissipates in an irreversible heat transfer process and that the greater the irreversibility, the more the entransy dissipates. Therefore, entransy is able to reflect any degradation in the grade of the energy from a heat transfer point of view [16].

A T-Q diagram is often applied to the analysis of entransy dissipation during the process of counterflow heat transfer, with the area between the two lines, which represent two flows of fluid contributing to the heat transfer, corresponding to the entransy dissipation [16]. In this respect, the T-Q diagram is a practical tool for application to the qualitative and quantitative analysis of grade loss, or entransy dissipation, in industrial waste heat recovery processes.

It can be proven that the optimal object of entransy dissipation minimization is equivalent to the optimal object of supply water temperature maximization, when only heat exchange processes are involved [8].