Applied Thermal Engineering 70 (2014) 1238–1245

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Design of solar collector networks for industrial applications

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HIGHLIGHTS

- A methodology for the design of solar collectors networks is introduced.
- Network structure represented by a series–parallel collector arrangement.
- Design approach based on a thermo-hydraulic model.
- Network of collectors determined based on the thermal and hydraulic needs.

ARTICLE INFO

Article history:
Received 7 January 2014
Received in revised form
28 April 2014
Accepted 1 May 2014
Available online 10 May 2014

Keywords:
Solar collector networks
Thermo-hydraulic model
Thermal length
Hydraulic length
Design space
Solar energy

ABSTRACT

The design and selection of banks of solar energy collectors for thermal applications requires that a thermal and a hydraulic objective be met. On the thermal side, the working fluid must provide the heat load to the process at the specified temperature and on the hydraulic side the fluid must flow through the system experiencing a pressure drop that is within the specified limits. In the case of solar collectors, the working fluid used to transfer heat to the process either in an open circuit or in a closed circuit is water. A solar collector can be viewed as a particular type of heat exchanger and the set of solar collectors needed for a particular application, as a network of heat exchangers. In this work, the overall arrangement of solar collectors which form the total collector surface area is referred to as the *network of solar collectors* (NSC). An NSC is used in large scale heating applications in buildings or in production processes. Such a network of collectors can exhibit arrangements that go from series, parallel or any combination of these. Contrary to domestic applications where water flows through the exchanger in natural convection, in large scale applications the flow of water is forced through the use of a pumping system. This paper introduces the tools for the design and selection of the most appropriate network arrangement for a given application as a function of the specified pressure drop for fluid flow, the required temperature and heat duty. A thermo-hydraulic model for solar collector networks is presented and its solution is graphically displayed with the length of the exchanger plotted against the number of arrays in parallel. The thermal and the hydraulic models are solved separately so that two solution spaces are represented in the same plot. The thermal space represents the thermal length required to meet the specified heat load as a function of the number of parallel arrays. The hydraulic space, on the other hand, represents the hydraulic length that meets the specified pressure drop as a function of the number of parallel arrays. The point where the two spaces meet determines the network structure that fulfils the required heat duty with an acceptable pressure drop.

1. Introduction

The use of heat from solar energy represents a clean and potentially economic hot utility source to meet the totality or part of the needs of low temperature industrial processes. If solar energy can only provide part of the heat duty of a process, the rest should be supplied by means of conventional sources of energy. The integration of solar thermal systems in process plants has two main design aspects: one of them is the design of the external solar facility that will carry out the duty of supplying the thermal needs of the process, and the other is the design of the internal network structure required for proper operation. The former problem refers to the design of the set of solar collectors and the latter to the design of the heat recovery system, including the storage system that will take into consideration operating variables such as time, which makes most low temperature processes, discontinuous in

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http://dx.doi.org/10.1016/j.applthermaleng.2014.05.005
1359-4311/

nature. This paper focuses on the design of the solar collector facility.

A solar collector is a type of heat exchanger where a working fluid absorbs energy from a solid surface exposed to solar radiation. The construction features of a solar collector depend on the desired temperature to be achieved. So, these types of equipment can broadly be classified into: low temperature, medium temperature and high temperature. In this work we concentrate on low temperature solar collectors where the maximum temperature achieved by the working fluid is below 100 °C. The thermal characterisation of these types of devices is based on the determination of the collector efficiency and the heat losses to ambient. Growing interest in reducing the capital cost of these systems has concentrated research efforts on increasing the thermal efficiency in combination with the efficient use of materials of construction as demonstrated by Eisenmann et al. [1].

The use of solar energy for domestic applications has a long story of application; however, in the case of industry the documented cases are not as common. Liu et al. [2] studied the application of solar heating systems for industrial applications where a considerable amount of hot water is required. In their study they considered the use of a set of solar collectors arranged in series and the system was experimentally tested to check for its sufficiency in supplying the required heat load. Zago et al. [3] conducted an investigation on the energy efficiency of independent and centralised heating systems considering the integration of solar plants; they determined the auxiliary energy consumption such as pumping power and demonstrated how this additional energy consumption tends to reduce the overall energy efficiency in buildings. Similar applications were reported by Lin et al. [4] who carried out an experimental study on solar heating applications in dormitories, swimming pools, restaurants, and manufacturing plants. An installation with an arrangement of three parallel sets of collectors was experimentally investigated. The network structure used in their work is as follows: two cascade arrangements with a six-series-collector array each and one with a four-series-collector array. The study refers to the thermal analysis of existing installations and no hydraulic analysis is conducted; besides no explanation is given regarding how the actual collector structure was chosen. A detailed application of solar energy into existing processes was reported by Quijera et al. [5,6]. Their work concentrated on the thermal analysis and the economics for fuel substitution in a fish canning company. In their work, the selection of the network of solar collectors required to provide the heat duty is based only on the thermal needs. Similar examples of the use of a wider spectrum of renewable energies such as: solar, biomass, certain types of waste, and geothermal energy sources in a large scale meat company were reported by Kiraly et al. [7]. The integration of solar thermal energy in low temperature processes is not a trivial task for there is the time variable to be accounted for which calls for the consideration of thermal storage capacity. Looking inside a process, Walmsley et al. [8] have shown how to design the heat recovery loops for indirect heat transfer and the necessary thermal storage to make the use of solar energy reliable.

Atkins et al. [9] present a comprehensive thermal analysis of the potential use of solar energy in processing plants for the production of powder milk. Their work considers the thermal analysis of evacuated solar collectors in a graphical way where authors display the effect of various operating conditions such as solar radiation, water mass flow rate and water outlet temperature on the heat load. As for the network of solar collectors required for the duty, it is only stated that the optimal configuration falls between two extremes: the pure series and the pure parallel arrangement and they propose a network comprising 100 parallel branches with five collectors in series each.

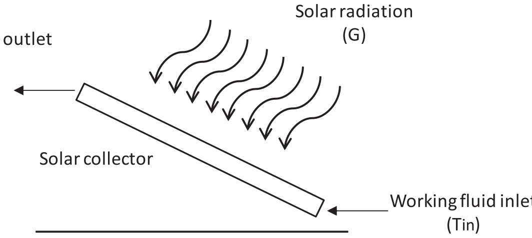

Fig. 1. Basic operating principles of a solar collector.

Earlier attempts to investigate the most appropriate solar collector network structure were reported by Garg [10] who studied some aspects of the design of solar water heaters suitable for the large and intermittent demands for hot water in hospitals and hotels. He experimentally analyzed various arrangements for connecting the field of solar collectors such as cascade, series, series–parallel and true parallel. From his results a system with a large number of solar collectors finds the maximum efficiency and economy when the arrangement is true parallel. Karagiorgas et al. [11] performed an economic evaluation of industrial applications of solar thermal installations in Greece. They analyzed the case of applications in the food industry, agro-industries, textiles and chemical industry. In their work they do not make reference to the actual arrangement of the bank of solar collectors and the installed surface area goes from 50 m^2 to 2700 m^2. On the hydraulic side, examples of the consideration of the study of pressure drop and power consumption at the design stage of water distribution in water networks are the work by Carravetta et al. [12]. This work examines how energy savings can be achieved by exploiting pressure drop by means of a control strategy in a series–parallel hydraulic circuit.

Heat exchangers are designed by the reconciliation of the physical dimensions that meet two fundamental goals: the thermal, given by the required heat duty and the hydraulic given by the specified pressure drops [13,14]. Solar collectors, being a type of heat exchanger are not the exception when it comes to design. To date, the thermal design solar collector is well developed and of the domain of many researchers and manufactures; however, there still remains the hydraulic aspect to be brought into consideration particularly in industrial applications where the mass flow rate of the working fluid is large and pumping power becomes an important operating cost.

The purpose of this work is to show how to undertake a thermo-hydraulic design for the determination of the arrangement of the network of solar collectors that will meet a required heat load and

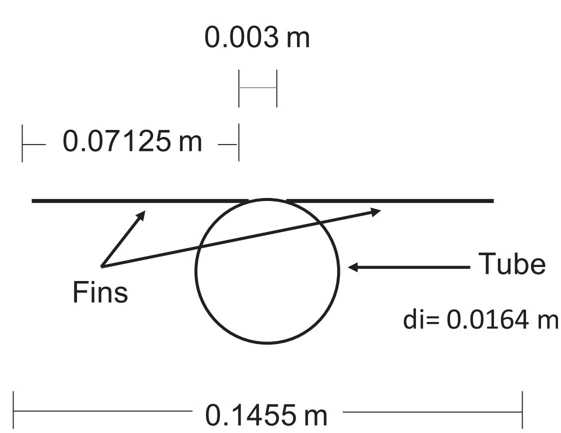

Fig. 2. Detail of the fin assembly in a single tube.