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Development of a computer program for the simulation of ice-bank system operation, part II: Verification

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ABSTRACT

In order to verify the mathematical model of an ice bank system developed for the purpose of predicting the system performance, experimental measurements on the ice bank system were performed. Static, indirect, cool thermal storage system, with an external ice-on-coil building/melting was considered. Cooling energy stored in the form of ice by night is used for the rapid cooling of milk after the process of pasteurization by day. The ice bank system was tested under real operating conditions to determine parameters such as the time-varying heat load imposed by the consumer, refrigeration unit load, storage capacity, supply water temperature to the load and to find charging and discharging characteristics of the storage. Experimentally obtained results were then compared to the computed ones. It was found that the calculated and experimentally obtained results are in good agreement as long as there is ice present in the silo.

Développement d'un logiciel pour la simulation du fonctionnement d'un système d'accumulation de glace. Partie II : vérification

Mots clés : Accumulation thermique ; Bac à glace ; Refroidissement ; Lait; ; Expérimentation ; Modélisation ; Simulation ; Comparaison

1. Introduction

In the past, several attempts were made to build and test dynamic mathematical models of an ice bank system. The static thermal storage systems which are most often quoted in literature are those classified as direct, external ice-on-coil (Finer et al., 1993; Lopez and Lacarra, 1999; Lee and Jones, 1996a,b) or internal ice-on-coil ice bank systems (Chaichana et al., 2001). Finer et al. (1993) and Lopez and Lacarra (1999) developed simple mathematical models of direct, ice-on-coil ice bank systems. Finer et al. (1993) came to the conclusion that for the cases when heat release by the user changes

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Nomenclature

A	surface area [m^2]
c_p	specific heat capacity [J kg^{-1} K^{-1}]
k	overall heat transfer coefficient [W m^{-2} K^{-1}]
$\dot{m}$	mass flow rate [kg s^{-1}]
M	mass [kg]
t	time [s]
Greek symbols	
α	heat transfer coefficient [W m^{-2} K^{-1}]
ϑ	temperature [°C]
Φ	heat transfer rate [W]
Subscripts	
b	secondary working fluid
ice	ice
in	inlet
M	mass
out	outlet
w	water
ϑ	temperature

relatively slowly with time, heat transfer can be considered as the process limiting factor. This assumption allowed them to neglect hydrodynamic aspects of the refrigeration unit performance and to build an ice bank model solely by energy balance relations. This was confirmed experimentally as correct except for the period immediately after the start-up. Likewise, Lee and Jones (1996a) developed analytical models for an indirect, ice-on-coil thermal energy storage system for both the charging and discharging modes. As such, the models were simplified to a large extent. Nevertheless, the error analysis indicated that model predictions were within 5% and 12% of experimental values. In addition, Lee and Jones, (1996b) conducted laboratory tests on a direct, ice-on-coil thermal energy storage system for air-conditioning applications and offered a basis for performance rating procedures for residential and light commercial CTES systems.

All the models presented in the above quoted publications have one thing in common: they were built for a specific case with a limited flexibility in the definition of design parameters and operating conditions. In order to allow a definition of numerous design parameters and operating conditions and still provide results with sufficient accuracy, a more complex computer model of a static, indirect, cool thermal storage system with an external ice-on-coil building/melting was developed (Halasz et al., 2009).

In the first part of this study, performance testing of an indirect ice-on-coil ice bank system is outlined, while in the second part, a validation of the developed mathematical model is discussed.

2. Experimental details

2.1. *Experimental apparatus and instrumentation*

The ice bank system under consideration, designed and manufactured by the company Frigoterm, was installed in the dairy "Antun Bohnec" in the city of Ludbreg, the Republic of Croatia, as a part of production line. It is a static, indirect, cool thermal storage with an external ice-on-coil building/melting, where ice is built up around the tubes by the secondary working fluid circulating through the tubes (which is cooled by the refrigeration unit). The ice bank system consists of the refrigeration unit cycle, the storage unit, i.e. ice silo, and the consumer cycle, Fig. 1.

The storage unit is a vertical cylindrical silo built as a stack of two equal modules. The outer part of the silo (of annular cross-section) is used for the ice build up or melting during the upward flow of water and the central part is used for the downward recirculation of water by means of a propeller (agitator). The agitator (nominal capacity of 300 m^3/h) was in operation only during the discharging mode and it was idle during the charging time.

Within each module, in the outer annular part, pipes for the flow of secondary working fluid are spirally wound in a horizontal plane. Each pipe has its own plane. The two vertically adjacent spirals form a staggered arrangement for the upward flow of water. Submerged pipe coils, with a secondary fluid flow, are used to build up ice on their outer surface. The pipes are made of polypropylene.

On the secondary coolant side, modules are connected in parallel so that the total flow of cold secondary working fluid coming from the refrigerating unit is distributed between the modules and later collected to be returned to the refrigerating unit. The secondary working fluid used was a glycol-water mixture (30% of ethylene glycol). In the consumer loop, the chilled water is circulated from the ice silo to a plate heat exchanger in the production line to provide milk cooling. The heated return water from the consumer is returned to the base module of the silo to be mixed with the chilled silo recirculation water.

Process variables, i.e. temperatures, flow rates and pressures are measured at several locations in the system, as indicated in Fig. 1. In the secondary fluid loop, two temperatures and one flow rate were measured, i.e. secondary working fluid temperatures at the silo inlet and outlet and the total secondary working fluid flow rate through the silo. Four thermocouples were used for this purpose. Two of them were bonded on the outer wall of a pipe (a steel pipe with the outside diameter of 89.7 and the wall thickness of 2.9 mm) just after the mass flow meter and before the secondary working fluid distribution joint to all modules. The other two thermocouples were placed in the same manner as the previous ones at a distance of 20 outer pipe diameters after the secondary working fluid collector joint of the modules. The pipe section with attached thermocouples was heavily insulated on the outside to prevent the influence of the environment and to make sure that the measured temperature was close enough to the temperature of the fluid flowing through the pipe. The measurement of the secondary working fluid flow rate was carried out with a vortex flow meter. It was installed in the secondary working fluid distribution line at a safe distance from the pump and bends.

In the chilled water cycle (consumer loop), two temperatures and one flow rate were measured, i.e. the chilled water temperature at the silo outlet and the warm return water temperature at the silo inlet, and the total chilled water flow