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Experimental and theoretical investigations of solidification and melting of ice for the design and operation of an ice store

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ABSTRACT

The Institute for Thermodynamics and Thermal Engineering (ITW) of the University of Stuttgart has developed a novel solar powered 10 kW absorption chiller. This chiller was implemented in the cooling system of the institute's building. To achieve a higher efficiency of the cooling system and to extend the hours of operation, a small ice store was designed, constructed and experimentally investigated. The experimental investigations include charging and discharging processes at different inlet temperatures and for different heat exchanger areas. For theoretical investigations a simulation program was developed and validated. Based on the results of these investigations a final heat exchanger design was established. In a further step the ice store was integrated into the building's cooling system. Long term measurements of the cooling system have shown good in-service behaviour of the ice store which fits the specific requirements of the cooling system in combination with the absorption chiller quite well.

Recherches expérimentales et théoriques sur la solidification et la fusion de glace pour la conception et exploitation d'un système à accumulation de glace

Mots clés : Refroidissement ; Énergie solaire ; Accumulation ; Glace ; Congélation ; Fusion

1. Introduction

Air conditioning and cooling of buildings are responsible for an increasing consumption of electrical energy. The main reason is a rising demand for comfort in commercial as well as private environments. Another reason is the growing number of buildings with a high glazing fraction in modern architecture.

To decrease the electrical demand of such systems solar cooling could become a serious alternative due to the fact that demand of cooling energy and solar energy supply match quite well in time. Therefore, significant development work has started in the last few years.

The Institute for Thermodynamics and Thermal Engineering (ITW) of the University of Stuttgart has focused some

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Nomenclature

COP	coefficient of performance, -
$\dot{Q}_{cond}$	conductive heat flow rate, W, 1 W = 1 Js^{-1}
$\dot{Q}_{lat}$	latent heat flow rate, W, 1 W = 1 Js^{-1}
$\dot{Q}_{conv}$	convective heat flow rate, W, 1 W = 1 Js^{-1}
Δh_s	latent heat of solidification, kJ kg^{-1}
Δh_s^*	effective latent heat of solidification, kJ kg^{-1}
a	thermal diffusivity, $m^2\ s^{-1}$
A_{ice}	outer surface of ice layer, m^2
c_p	specific heat capacity, kJ $kg^{-1}\ K^{-1}$
d	outer tube diameter, m
g	acceleration due to gravity, ms^{-2}
Gr	Grash of number, -
U	Overall heat transfer coefficient, $Wm^{-2}\ K^{-1}$
L_{tube}	length of tube, m
$L_{tube,\ vert}$	length of the vertical part of the tube, m
m_{ice}	mass of ice, kg
N	number of meanders, -
Nu	Nusselt number, -
Ph	phase transition number, -
Pr	Prandtl number, -
Q	heat, transferred Energy, kWh
R	radius of the tube, m
Ra	Rayleigh number, -
r_{ice}	radius of the ice cylinder, m
St	Stephan number, -
s_W	characteristic length, m
α	heat transfer coefficient, $Wm^{-2}\ K^{-1}$
β	coefficient of thermal expansion, K^{-1}
ϑ_∞	temperature of the liquid water, °C
ϑ_s	temperature at the ice surface, °C
ϑ_W	temperature of water at heat transfer surface, °C
ϑ_{wall}	temperature at the outer tube wall, °C
λ_{ice}	thermal conductivity of ice layer, $Wm^{-1}\ K^{-1}$
ν_W	kinematic viscosity, $m^2\ s^{-1}$
ρ_{ice}	density of ice, kg m^{-3}

Indices

c	cooling
ct	coolant
cond	conduction
conv	convection
crit	critical
equ	equivalent
ice	ice mass/ice layer/solid phase of storage mass
i	in, inside
it	inside of tube
k	time step
l	liquid
lat	latent
mod	modified
o	out, outside
ot	outside of tube
s	solid
sen	sensible
sur	surface
tube	heat exchanger tube
w	water/liquid phase of storage mass
wall	outer tube wall
water	water/liquid phase of storage mass

of its research activities on the development of an absorption chiller with a cooling capacity of 10 kW at standard conditions. At these standard conditions the heating inlet temperature at the generator is 100 °C. The inlet temperature of the condenser and the absorber is 27 °C. The outlet temperature of the evaporator is 15 °C (Zetzsche et al., 2007). The working pair ammonia/water allows evaporator temperatures lower than 0 °C and hence the formation of ice.

The ice store was designed as a back-up system to support the absorption chiller mentioned above. From an exergetical point of view, the temperature level provided by the ice store is critical. There is a wide gap between cooling temperatures at approximately 16–18 °C and the ice temperatures equal or lower than 0 °C. But the advantages of the ice store are predominant. Cooling energy can be stored in a compact volume due to the phase change of water. Water is a cheap storage medium which is not at all harmful to the environment. With this arrangement it is possible to provide cooling energy even if the chiller is not working, for example because of insufficient radiation. It is also possible to run the absorption chiller when there is no cooling demand of the building, for example on weekends or public holidays. The hours of operation of the absorption chiller are thus extended. The cooling requirement of the rooms is met either by the absorption chiller or by the ice store. Finally, it is also possible to use the ice store to support the absorption chiller, if higher cooling requirements are necessary to cool the rooms than the absorption chiller is able to deliver.

The aim of this project is to apply the cooling system to small offices and domestic buildings. Therefore, the components have to have a compact size; the ice store has been limited to a maximum volume of 0.5 m^3.

It is essential that the ice store achieves high charging and discharging rates, and a high volumetric capacity despite its small size. To reduce the electrical energy demand of the cooling system, no electrically powered equipment such as mixer or additional air injection was implemented. In general, such equipment is used to increase the turbulence of the liquid phase and, therefore, improve the heat transfer.

The aim of the present experimental investigation was to show the heat transfer capacity of the ice store at inlet temperatures from −4 to −10 °C in charging mode and inlet temperatures from 20 °C at discharging mode. Also, the influences of heat transfer area and different operational discharging modes on the capacity were investigated. This study presents and discusses the measured data of the associated experiments.

In additional to the experimental data, methods to calculate charging procedures are described. The calculations were validated with the experimental data.

Ice stores use the phase change of water to ice and have therefore a high volumetric storage capacity. The specific