INTERNATIONAL JOURNAL OF REFRIGERATION 57 (2015) 87–93

Available online at www.sciencedirect.com

ScienceDirect

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

Simulation based identification of the ideal defrost start time for a heat pump system for electric vehicles

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ARTICLE INFO

Article history:
Received 7 January 2015
Received in revised form
15 April 2015
Accepted 26 April 2015
Available online 8 May 2015

Keywords:
Air-to-air heat pump
Defrost
Hot gas bypass
Electric vehicle
Carbon dioxide
Simulation

ABSTRACT

Resistance heating with PTC elements to cover the heat demand of electric vehicles reduces significantly the cruising range at low outside temperatures. Reversible heat pump systems are one of the most promising solutions for this problem. However, in heat pump mode the frost formation on the exterior heat exchanger reduces the performance and efficiency of the system. Therefore, an efficient defrost method is crucial to benefit from the heat pump also under frosting conditions. In the present paper, a transient Modelica simulation model of a reversible CO_2-heat pump system with hot gas defrost was set up in order to assess the impact of different defrost start times. The model is able to handle frost growth on the exterior heat exchanger as well as defrosting. The simulation results showed an optimal point of time to conduct defrost at chosen operating conditions in order to maximize the average COP including the frosting and defrost period.

Identification par simulation du moment idéal de début de dégivrage pour un système de pompe à chaleur pour véhicules électriques

Mots clés : Pompe à chaleur air-air ; Dégivrage ; Bypass à gaz chaud ; Véhicule électrique ; Dioxyde de carbone ; Simulation

1. Introduction

Compared to conventional vehicles, electric vehicles have less waste heat available for heating the passenger compartment. Thus, additional heat sources are required to cover the heat demand at low ambient temperatures. Whereas resistance heating with PTC elements reduces significantly the cruising range of electric vehicles, the use of the A/C system with CO_2 as refrigerant as a air-to-air heat pump is a much more energy efficient solution.

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http://dx.doi.org/10.1016/j.ijrefrig.2015.04.018
0140-7007/

Nomenclature

A	Area [m^2]
ASHP	Air source heat pump
COP	Coefficient of performance
c_p	Specific heat capacity [J $(kg\ K)^{-1}$]
d_h	Hydraulic diameter [m]
EHX	Exterior Heat Exchanger
h	Specific enthalpy [J kg^{-1}]
IHX	Interior Heat Exchanger
J	Colburn factor
Kv	Flow coefficient [$m^3\ h^{-1}$]
Le	Lewis number
$\dot{m}$	Mass flow rate [kg s^{-1}]
n	Engine speed [s^{-1}]
Nu	Nusselt number
P	Power [W]
Pr	Prandtl number
PTC	Positive Temperature Coefficient
$\dot{Q}$	Heat Flow [W]
Re	Reynolds number
t	Time [s]
$T_{f,s}$	Frost surface temperature [K]
V	Volume [m^3]
x	Vapour quality
x_a	Water load of moist air [kg kg^{-1}]
$x_{s,wall}$	Saturation water load at frost/wall surface [kg kg^{-1}]

Greek symbols

α	Heat transfer coefficient [W $(m^2\ K)^{-1}$]
β	Mass transfer coefficient [m s^{-1}]
δ_f	Frost thickness [m]
Δh_{lv}	Specific heat of vaporisation [J kg^{-1}]
Δh_{sl}	Specific heat of fusion [J kg^{-1}]
η_{ei}	Effective isentropic efficiency
η_{is}	Isentropic efficiency
λ	Volumetric efficiency
λ_f	Thermal conductivity of frost [W $(m\ K)^{-1}$]
ρ	Density [kg $(m^3)^{-1}$]
ρ_a	Moist air density [kg $(m^3)^{-1}$]
$\rho_{f,avg}$	Average frost density [kg $(m^3)^{-1}$]
$\rho_{f,s}$	Frost surface density [kg $(m^3)^{-1}$]

Subscripts

avg	Average
cond	Condensation
eff	Effective
f	Frost
in	Inlet
is	Isentropic
lat	Latent
lv	Liquid-vapor
out	Outlet
sens	Sensible
sl	Solid-liquid

In heat pump mode the exterior heat exchanger (EHX) works as refrigerant evaporator. At low ambient temperatures the evaporation temperature can drop below 0 °C, which therefore leads to a surface temperature of the evaporator lower than the freezing point of water. This is the precondition for the formation of frost on the heat exchanger. Due to it's low thermal conductivity, the growing frost layer decreases the performance of the EHX, which leads to a decline of the heating capacity as well as the COP of the heat pump. Therefore, defrosting of the EHX is necessary from time to time and an efficient defrost method is crucial to benefit from the heat pump also under frosting conditions. Dong et al. (2012) mentioned measurement results where defrost energy consumption accounted for 10% of the total energy consumption of a stationary air source heat pump during heating operation.

Considering energy efficiency, defrost methods which remove the frost by passing hot refrigerant through the EHX are supposed to be the most effective ones (Ding et al., 2004). The two established methods using this principle are:

- Reverse cycle defrost: By using a high- and low-pressure switching valve, the refrigerant cycle can be switched from heating to cooling mode. Whereas in heating mode the EHX works as evaporator and frost can form on it, in cooling mode it works as gascooler (supercritical operation) or condenser (subcritical operation). Thus, hot high-pressure refrigerant from the compressor enters the EHX to melt the frost.
- Hot gas defrost: Via a by-pass valve the hot gas from the compressor is directly expanded and passed to the EHX to melt the frost.

The reverse cycle defrost method has the advantage of higher heating (defrost) performance because the ambient air is used as heat source, whereas the hot gas defrost uses only the heat from the compressor. But major drawbacks of the reverse cycle method applied in a car are the possible water condensation or frost formation on the IHX during defrost, which supports flash fogging when switching back to heating mode (Peters, 1972). Further, the cold air exiting the IHX can not be blown into the vehicle cabin without dramatically reducing thermal comfort. Therefore, an additional mechanism in the HVAC box is necessary to pass the outcoming air of the IHX to the ambient. Hot gas defrost does not have the mentioned drawbacks of reverse cycle defrost, but additional solenoid valves are needed in order to enable a redirection of the refrigerant in heating mode to the bypass valve.

In contrast to mobile air conditioning where publications on this topic are rare, several studies were performed for domestic refrigeration systems. E.g. Liu et al. (2003) showed simulation results of a model of an air-source heat pump during hot-gas defrost. Dopazo et al. (2010) predicted the required time and needed energy of the hot-gas defrost process of an air-coil evaporator using a transient simulation model and validated it with experimental data. But none of these models was able to handle frosting as well as defrosting.

As frosting and defrosting are inherently transient phenomena, steady state models which are often used to predict the heat pump performance are not suitable to give adequate