Transportation Research Part D 48 (2016) 316–331

Contents lists available at ScienceDirect

Transportation Research Part D

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

Life cycle assessment of heated apron pavement system operations

Weibin Shen [a], Halil Ceylan [b], Kasthurirangan Gopalakrishnan [c,*], Sunghwan Kim [d], Peter C. Taylor [e], Chris R. Rehmann [f]

[a] 24 Town Engineering Building, Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA 50011, USA
[b] 406 Town Engineering Building, Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA 50011, USA
[c] 354 Town Engineering Building, Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA 50011, USA
[d] 24 Town Engineering Building, Institute for Transportation, Iowa State University, Ames, IA 50011, USA
[e] National Concrete Pavement Technology Center, Iowa State University, Ames, IA 50011-3232, USA
[f] 482B Town Engineering Building, Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA 50011, USA

ARTICLE INFO

Article history:
Available online 27 August 2016

Keywords:
Greenhouse gas
Energy
Pavements
Snow and ice
Heating
Sustainability

ABSTRACT

Heated pavement systems (HPS) offer an attractive alternative to the cumbersome process of removing ice and snow from airport pavements using traditional snow removal systems. Although snow and ice removing efficiency and economic benefits of HPS have been assessed by previous studies, their environmental impact is not well known. Airport facilities offering public or private services need to evaluate the energy consumption and global warming potential of different types of snow and ice removal systems. Energy usage and emissions from the operations of hydronic heated pavement system using geothermal energy (HHPS-G), hydronic HPS using natural gas furnace (HHPS-NG), electrically heated pavement system (EHPS), and traditional snow and ice removal system (TSRS) are estimated and compared in this study using a hybrid life cycle assessment (LCA). Based on the system models assessed in this study, HPS application in the apron area seems to be a viable option from an energy or environmental perspective to achieve ice/snow free pavement surfaces without using mechanical or chemical methods. TSRS methods typically require more energy and they produce more greenhouse gas (GHG) emissions compared to HPS during the operation phase, under the conditions and assumptions considered in this study. Also, HPS operations require less energy and have less GHG emissions during a snow event with a smaller snowfall rate and a larger snow duration.

1. Introduction

The global climate change is likely to lead to lower average temperatures in the mid-west and northeast parts of the United States as well as more frequent winter precipitation events. Therefore, the use of life-cycle assessment (LCA) methodology to identify the appropriate technology to help airports adapt to climate change while also mitigating future emissions is warranted. A primary objective of the U.S. Federal Aviation Administration's (FAA's) Next Generation Air Transportation System (NextGen), currently being implemented in stages, is to reduce delays and interruptions to flight operations.

* Corresponding author.
E-mail addresses: wshen@iastate.edu (W. Shen), hceylan@iastate.edu (H. Ceylan), rangan@iastate.edu (K. Gopalakrishnan), sunghwan@iastate.edu (S. Kim), ptaylor@iastate.edu (P.C. Taylor), rehmann@iastate.edu (C.R. Rehmann).

http://dx.doi.org/10.1016/j.trd.2016.08.006
1361-9209/

Nomenclature

A_r	ratio of snow-free area to total area, dimensionless
C	specific heat of concrete pavement, kJ/kg °C or Btu/lb °F
COP	coefficient of performance of geothermal heat pump, decimal number
c_1	conversion factor, 1000 mm/m or 12 in./ft
$c_{p,ice}$	specific heat of ice, kJ/kg °C or Btu/lb °F
$c_{p,water}$	specific heat of water, kJ/kg °C or Btu/lb °F
δ	Stephan-Boltzmann constant, Btu/h ft^2 °R^4
ΔT	temperature difference, °C or °F
E	Energy consumption of geothermal heat pump, Btu/h or kJ/h
ε_s	emittance of wet slab, dimensionless
H	total head, ft
h_c	convection heat transfer coefficient for turbulent flow, Btu/h ft^2 °F
h_f	heat of fusion for water, kJ/kg or Btu/lb
h_{fg}	heat of evaporation at the film temperature, kJ/kg or Btu/lb
h_m	mass transfer coefficient of concrete slab, m/h or ft/h
M	mass of concrete pavement, kg or lb
MU	flow rate increase multiplier, 0.085 for 40% by volume glycol mixture
n	pump efficiency, decimal number
P	power required for circulating pump, hp
ρ_{dry_air}	density of dry air, kg/m^3 or lb/ft^3
ρ_{water}	density of water equivalent of snow, kg/m^3 or lb/ft^3
Q	flow rate, gallon/min
Q_t	total heat rate required for pavement idling and snow melting, Btu/h or kJ/h
q_h	heat transfer rate by convection and radiation, Btu/h ft^2 or kJ/h m^2
q_e	heat rate of evaporation, Btu/h ft^2 or kJ/h m^2
q_i	heating rate required for concrete pavement idling, Btu/h or kJ/h
q_m	heat rate of fusion, Btu/h ft^2 or kJ/h m^2
q_o	heat rate required for melting snow using heated pavement system, Btu/h ft^2 or kJ/h m^2
q_s	sensible heat rate transferred to the snow, Btu/h ft^2 or kJ/h m^2
SG	specific gravity of heated solution, 1 of water and 1.034 of 40% propylene glycol
s	rate of snowfall, mm or inches of water equivalent per hour
T_f	liquid film temperature, °R
T_{MR}	mean radiant temperature of surroundings, °R
t	snow period, h
t_a	ambient temperature coincident with snow fall, °C or °F
t_f	liquid film temperature, °C or °F
t_s	melting temperature, °C or °F
W_a	humidity ratio of ambient air, lb_{vapor}/lb_{air}
W_f	humidity ratio of saturated air at film surface temperature, lb_{vapor}/lb_{air}

Traditional snow and ice removal methods could cause airline delays, high operation costs and airside incidents involving airport crew during snow and ice removal activities. In order to prevent these problems, heated pavement systems (HPS) are being studied as an alternative strategy, in the context of FAA's NextGen and efficient adaptation to climate change, to traditional snow and ice removal systems (TSRS) applied in apron areas (Ceylan, 2015). Shen et al. (2015) recently reported that hydronic HPS, the most common type of HPS, could have environmental benefits when used to remove snow and ice from aprons.

The primary goal of this study is to provide a more comprehensive understanding of different snow and ice removal system (SRS) operations not only from an energy consumption perspective but also from an environmental impact aspect and to help the airport authorities make a more informed decision. To accomplish this goal, this study aims to identify the inventories or steps that burden each SRS operation the most so that energy usage and environmental impacts can be reduced. The energy consumption and contributions to global warming of four snow and ice removal systems as applied to the airport apron are evaluated and compared for different snowfall conditions. These systems are hydronic HPS using geothermal energy (HHPS-G), hydronic HPS using natural gas furnace (HHPS-NG), electrically heated pavement system (EHPS) using electricity, and TSRS. Heating energy sources are the primary differences among HPS types evaluated.

As one of the first life cycle assessment (LCA) studies on different types of HPS, this paper focuses on the impacts of HPS operation phase and related life cycle stages in comparison to TSRS. For simplicity, system boundaries of four different SRS include only sectors defined as processes of snow and ice removal operation. SRS can be generally classified into four sub-system processes: power generation, material production, snow and ice removal application, and waste treatment.