Energy Conversion and Management xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Exergoeconomic optimization of coaxial tube evaporators for cooling of high pressure gaseous hydrogen during vehicle fuelling

Jonas K. Jensen *, Erasmus D. Rothuizen, Wiebke B. Markussen

Technical University of Denmark, Department of Mechanical Engineering, Nils Koppels Alle, Building 403, DK – 2800, Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Exergoeconomic optimization
Evaporator design
Heat transfer modelling
Hydrogen fuelling
Hydrogen fast filling

ABSTRACT

Gaseous hydrogen as an automotive fuel is reaching the point of commercial introduction. Development of hydrogen fuelling stations considering an acceptable fuelling time by cooling the hydrogen to −40 °C has started. This paper presents a design study of coaxial tube ammonia evaporators for three different concepts of hydrogen cooling, one one-stage and two two-stage processes. An exergoeconomic optimization is imposed to all three concepts to minimize the total cost. A numerical heat transfer model is developed in Engineer Equation Solver, using heat transfer and pressure drop correlations from the open literature. With this model the optimal choice of tube sizes and circuit numbers are found for all three concepts. The results show that cooling with a two-stage evaporator after the pressure reduction valve yields the lowest total cost, 45% lower than the highest, which is with a one-stage evaporator. The main contribution to the total cost was the cost associated with exergy destruction, the capital investment cost contributed with 5–14%. The main contribution to the exergy destruction was found to be thermally driven. The pressure driven exergy destruction accounted for 3–9%.

1. Introduction

Fossil fuel depletion and carbon-dioxide emission are two of the main factors that must be considered when assessing energy for private transport. A transition from fossil fuels to renewable and zero emission energy is a requirement for the development of a sustainable transport sector. Introducing hydrogen as a fuel for private transportation is one measure for addressing these issues. In recent years research and development on gaseous hydrogen fuel cell vehicles has matured the technology to the point of commercial introduction. This coming fleet of hydrogen vehicles will require a hydrogen infrastructure that includes hydrogen fuelling stations. The development of hydrogen fuelling stations has two often opposing objectives: low energy consumption and high customer acceptance, the former to comply with the sustainability aspect, the latter to compete with conventional petrol or diesel fuelling.

Hydrogen vehicles reach a tank pressure of 70 MPa after fuelling from a hydrogen bank maintained at 90 MPa [1] or through a cascade fuelling system [2]. To regulate the fuelling duration an actuated pressure reduction valve is placed in the hydrogen dispenser. This valve maintains a linear pressure increase in the vehicle's hydrogen tank. To compete with conventional fuelling the duration must be as short as possible. Conversely, if the fuelling duration is too short it will lead to overheating of the tank. The heat is generated by three phenomena [3,4]: the heat of compression, the conversion of kinetic to internal energy and the negative Joule–Thomson coefficient of hydrogen. The negative Joule–Thomson coefficient causes a temperature increase of hydrogen when it is subjected to a forced adiabatic expansion.

The fuelling duration can be reduced without overheating the hydrogen tank by cooling the hydrogen before it enters the vehicle [5]. The relation between fuelling duration and cooling temperature is given by SAE-tir-J2600 [6] and SAE-tir-J2601 [7]. For hydrogen vehicles with tank capacities of 1–7 kg a cooling temperature of −40 °C is advised. To reduce the energy consumption required to attain this, the refrigeration system should be designed to minimize the exergy destruction within it. A reduction of exergy destruction in a vapour compression refrigeration system is best achieved by improving the evaporator, as the endogenous avoidable exergy destruction is highest in this component [8].

The recent research and development in hydrogen fuelling has been focused in part on the physical phenomenon under fast filling of hydrogen tanks [3–5,9] and in part on the overall energy efficiency of hydrogen fuelling stations [1,2]. Although SAE-tir-J2600 [6] and SAE-tir-J2601 [7] state that cooling is required little research has been published on how these refrigeration systems

* Corresponding author. Tel.: +45 45251968;fax: +45 45884325.
E-mail addresses: jkjje@mek.dtu.dk (J.K. Jensen), edro@mek.dtu.dk (E.D. Rothuizen), wb@mek.dtu.dk (W.B. Markussen).

http://dx.doi.org/10.1016/j.enconman.2014.02.023
0196-8904/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

Symbols

C	Cost ($)
D	Diameter (m)
E	Exergy (kW)
I	Life time (years)
L	Length (m)
LS	High-stage load-share (–)
N	Number of tube in tube circuits (–)
T	Temperature (°C)
UA	Over all heat transfer coefficient (kW/m^2 K)
V	Volume (m^3)
$\dot{Q}$	Heat load (kW)
$\dot{m}$	Mass flow rate (kg/s)
c	Specific cost ($/kg)
e	Specific exergy (kW/kg)
f	Exergoeconomic factor (–)
h	Specific enthalpy (kj/kg)
k	Conductivity (kW/m K)
n	Number of (–)
p	Pressure (atm)
r	Interest rate (–)
r	Real roughness of pipe (–)
s	Specific entropy (kj/kg K)
t	Pipe wall thickness (m)
x	Vapour mass fraction (vapour quality) (–)

Abbreviations

COP	Coefficient of performance
CV	Control volume
EES	Engineering Equation Solver
HPS	Hydrogen pipe size
NPS	Nominal pipe size
RPS	Refrigerant pipe size

Greek letters

$\bar{\alpha}$	Average heat transfer coefficient (kW/m^2 K)
Δ	Difference
ϵ	Absolute roughness (m)
ρ	Density (m^3/kg)

Superscripts

CI	Capital investment
M	Mechanical
OP	Operation
PH	Physical
TI	Total investment
T	Thermal

Subscripts

0	Dead state
C1	Concept 1
C2	Concept 2
C3	Concept 3
c	Circuit
f	Fuel
hyd	Hydrogen
H	High-stage
in	Flow into control volume
i	Inner
j	jth stream
L	Low-stage
mat	Material
M	Mechanical
m	Minimum
oh	Operating hours (h)
opt	Optimal
out	Flow out of control volume
o	Outer
ref	Refrigerant
RV	Reduction valve
tot	Total

should be designed. Rothuizen et al. [10] investigated the use of an indirect refrigeration system with an acetate brine to cool hydrogen under fuelling. This has the advantage of storing cooling capacity in the brine but has the disadvantage of a large heat ingress to the tank and distribution system caused by the continuous circulation of the brine to prevent icy clods from plugging the system.

This study will investigate the use of a direct refrigeration system in which the hydrogen is cooled directly by an evaporative stream of refrigerant. A refrigeration system such as this can be run only when the station is fuelling and thus can reduce the energy consumption compared to an indirect system. Three concepts for applying direct evaporation refrigeration systems has been identified. The choice of evaporator design is highly influenced by the pressure of up to 90 MPa in the hydrogen supply system. This eliminates the application of typical heat exchanger designs such as brazed plate or plate and shell. It is a general assumption that all hydrogen conduits must be composed of high pressure pipes. The coaxial tube evaporator can be designed with these restrictions and is therefore chosen. Due to the Joule–Thomson effect the evaporator must be placed as close as possible to the exit of the station [7]. The evaporator must therefore be built into the hydrogen dispenser, which makes the size a constrained parameter.

The size of the evaporator is governed by the choice of design variables such as pipe dimensions and the number of parallel circuits. Size is typically minimized by increasing flow velocity but this will typically cause increased pressure loss. To find the best trade-off design between these opposing effects an exergoeconomic optimization is applied. Exergoeconomic optimization is a generalized method for minimization of the total cost of a component. It is described in literature by Tsatsaronis [11], Kotas [12] and Bejan et al. [13]. The exergoeconomic optimization method has been applied to determine optimal design variables for heat exchangers in [14–16]. The total cost of a component is comprised by the capital investment and maintenance cost, the so called non-exergetic cost, and the cost of thermodynamic irreversibilities i.e. exergy destruction. Thereby the exergoeconomic optimization is a multi-objective minimization of the non-exergetic and exergetic cost.

This study will seek to determine exergoeconomic optimum designs for three concepts of direct evaporation hydrogen cooling heat exchangers. The objective of the optimization is to minimize the total cost of an evaporator that meets the requirements of SAE-tir-J2601 [7] and SAE-tir-J2600 [6] and satisfies the spatial constraints. The optimization is subjected to three decision variables: the hydrogen pipe size, the refrigerant pipe size and the number of parallel circuits. Ammonia was chosen as the refrigerant as it has no ozone depletion potential and a global warming