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Review

Experimental study of inverse identification of unsteady heat transfer coefficient in a fin and tube heat exchanger assembly

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ABSTRACT

An inverse method is used to experimentally determine the transient heat transfer coefficient distribution over the fin of the second row of a staggered finned tube heat exchanger assembly. The experimental test bench uses an infrared thermography system that records the temperature drop of the circular fin surface during a transient experiment. Based on this unsteady temperature field, a specific inverse method has been developed in order to assess the heat transfer coefficient over the fin. The obtained results show the high accuracy of the inverse process in determining heat transfer coefficient spatial distribution which can be viewed as a "constant wall temperature heat transfer coefficient" over given interval in the experimental transient method.

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Nomenclature

c	specific heat (J kg^{-1} K^{-1})
Dt	tube diameter (m)
d	direction of descent
e_f	fin thickness (m)
$[E]$	matrix from FEM
$\boldsymbol{F}$	load column-vector from FEM
$[H]$	approximation of the Hessian matrix
h	heat transfer coefficient (W m^{-2} K^{-1})
J	cost function
$[K]$	stiffness matrix from FEM
$[M]$	mass matrix from FEM
n	unit normal vector
Ns	total number of finite element nodes
Nt	total number of time steps
S_Ω	surface of computation domain
T	temperature (K)
t	time (s)
x, y	coordinates system (m)

Greek symbols

ρ	density (kg m^{-3})
λ	thermal conductivity (W m^{-1} K^{-1})
ϕ	unknown boundary heat flux (W m^{-2})
Ω	computation domain
$\partial\Omega$	boundary of the computational domain
η	search step size
ε	emissivity
σ	Stephan–Boltzmann constant (W m^{-2} K^{-4})
σ_{err}	standard deviation of the measurement errors
ω	small real number
ψ	adjoint function
$\mathcal{L}$	Lagrangian
δ	Dirac delta function
∇	gradient operator
∇^2	Laplacian operator

Subscripts

conv	convection
e	entrance
f	final
i	initial
κ	iteration index
m	time step index
rad	radiation
ref	reference

Superscripts

$\wedge$	estimated values
$\star$	measured values
$'$	derivative symbol
T	transpose symbol

Abbreviations

DL	digital level
FEM	finite element method
HSV	horseshoe vortex
IR	infrared
VMM	variable metric method

1. Introduction

Heat exchangers play a key role in the operation of many engineering systems such as heat recovery units, process industries or automotive HVAC systems. Their optimization is then of major importance for energy savings and costs decreases. Increasing thermal efficiency of heat exchangers is often achieved through the enhancement of their global airside heat transfer. Today, CFD is an effective tool increasingly used to asses heat exchangers performances [1]. Anyway because of the complex flow structures involved with turbulent flow, transitional phenomena, turbulence spots, CFD approach and particularly RANS modeling is not always as accurate as needed. Experimental validation techniques estimating local distributions of convective flux would support numerical results and significantly help the design of these thermal components.

Fin-and-tube heat exchangers could have quite complex convection coefficient distribution far away from uniform distribution, due to the formation of horseshoe vortices (HSV) at each fin-tube junction [2–5]. These vortical flow structures lead to intensive heat transfer rates whereas recirculation zones downstream the tubes are less efficient. More over, alternative enhancement techniques consisting in generating secondary flows using some vortex generators that strongly modify the fluid flow structure also exist [6,7] and complex the heat transfer coefficient map. Nevertheless, in literature, it is very difficult to find experimental results presenting local heat transfer coefficient in fin-tube heat exchangers with sufficient resolution to detect accurately thermal imprints of convective structures.

A first set of methods consists of steady state experiments performed on test benches with generally prescribed heat flux boundary conditions. In [8], Huang et al. determined heat transfer coefficient distribution in a finned tube assembly using infrared thermography and an inverse scheme. For an other kind of heat exchanger (coiled tube), Bozzoli et al. [9] use an inverse heat conduction formulation to determined local heat transfer coefficient from IR thermography measurements. In both articles, the strong point of inverse techniques is that the estimate does not require a priori information for the functional form of the unknown heat transfer coefficient. The weaknesses of the steady state methods is that a uniform distribution of heat flux has to be generated by Joule effect making the solution sensitive to the prescribed boundary condition. Moreover, experimental measurements are often associated with noise measurement (IR measurements). In this case, the estimation of convective heat exchange at the fluid-solid interface requires a more or less important regularization depending of the value of the conductivity of the conductive material, which is not without consequence on the quality of the inversion (indeed, the higher the conductivity is, the more ill-posed the inverse problem becomes).

Transient techniques are more often used with simplified heat conduction models in order to find analytical expressions of steady heat transfer coefficient. Several research groups have designed experimental methods to examine local heat transfer rate in tube finned geometries. Tiggelbeck et al. [10], use a thermal transient method that exploits time temperature variation of a thin plate suddenly heated by convection using warm air. The convection coefficient is deduced using a time integration of the energy equation using the three following assumptions: conduction as well as radiation heat fluxes are negligible, and temperature is constant across the plate thickness. This last assumption is correct if the Biot number is under a value of 0.1. Kim et al. [11] used the same