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HEAT TRANSFER IN INDUSTRIAL FURNACES

ANNUAL REPORT

(April 1992 - March 1993)

Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631

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Prepared
by

H. Ramamurthy, S. Ramadhyani, P.F. Sullivan
and R. Viskanta

School of Mechanical Engineering
Purdue University
West Lafayette, IN 47907

for

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GRI Project Manager
Ferol Fish
Physical Sciences Department

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16. Abstract (Limit: 200 words)

The thermal system model for an indirectly-fired continuous furnace has been completed by coupling a one-dimensional radiant tube model with the furnace space model. For a given furnace geometry, it is now possible to specify the firing rates in individual radiant tubes and to predict the resulting load temperature profiles and heat transfer to the load while also calculating the exhaust gas temperature from each tube. Sensitivity studies have been performed, but the model has not been validated because of lack of appropriate test or operating furnace data.

A two-dimensional of the processes within a radiant tube has been developed to calculate the flame structure, the rate of fuel burn-up and the convective as well as radiative heat transfer from the combustion products in the tube to the walls. Model predictions have been compared with published experimental data for a tube with and without combustion for the purpose of validating the model.

The thermal system models for a directly-fired continuous furnace has been validated with available data from both experimental furnaces and full scale industrial furnaces. Predictions from the furnace model have compared quite favorably with available data.

As continuous activity to model directly-fired, high temperature industrial furnaces, an exhaustive literature survey was conducted to identify all possible sources of combustion and heat transfer data for validation of phenomenological physico-chemical and thermal system models.

17. Document Analysis a. Descriptors

Indirectly Fired Industrial Furnaces, Gas-Fired Radiant Tubes, Directly Fired Furnaces, Industrial and Metallurgical Furnaces

b. Identifiers/Open-Ended Terms

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RESEARCH SUMMARY

Title:	Heat Transfer in Industrial Furnaces GRI Contract No.: 5086-260-1293
Contractor:	Purdue University School of Mechanical Engineering
Principal Investigators:	R. Viskanta and S. Ramadhyani
Period:	April 1992 - March 1993

Annual Report

Objective: The objective of the project is to conduct analytical and theoretical research for predicting the thermal performance of indirectly and directly fired high-temperature industrial furnaces. Knowledge of heat transfer between the combustion products, intermediate load and ultimate load and between the combustion products and the load is necessary to improve understanding, control, and enhancement of furnace efficiency.

Technical Perspective: In spite of the fact that natural gas has been used as a fuel for many decades for indirectly and directly fired industrial and metallurgical furnaces, understanding of chemically reacting flows, turbulence, combustion, radiation and heat transfer processes in these furnaces is incomplete. Knowledge of heat transfer between the combustion products and intermediate and/or ultimate load is needed to improve the understanding, control and enhancement of furnace efficiency. Recent advances in computer hardware, computational algorithms, and radiation heat transfer are being used to enable simulation of complex combustion-heat transfer processes in furnaces and to improve technologies in the industrial sector.

Results: Directly-fired continuous furnace model prediction have been validated with data from two operating industrial furnaces and two experimental furnaces. Detailed results for each validation case are presented in this report.

Two literature reviews have been completed. The first reviews the data available for validating a variety of thermal system and detailed models of directly-fired furnaces. The second reviews the state of the art in modeling NO_x formation in nonpremixed combustion.

A thermal system model has been developed for a radiant tube, continuous furnace by coupling a one-dimensional radiant tube model to the furnace enclosure model. Model parameters and operating conditions can be easily varied in order to study their effects on the thermal performance of the furnace. Preliminary results obtained using the thermal system model with three different radiant tube designs are presented in this report.

A two-dimensional predictive model has been developed for radiant tubes to obtain the convective heat transfer rate to the tube wall and the rate of fuel burn-up within the tube. Several high and low Reynolds number turbulence models have been judged for their performance by comparing model predictions with measurements in fully developed pipe flows by Laufer and abrupt expansion pipe flows with heat transfer by Baughn et al. (1986). The two-dimensional model has also been validated by comparing model predictions with measurements in gas combustor flows by Bowman et al. (1975) and Spadacini et al. (1976).

Technical Approach: The physical processes occurring in the furnace are modeled by equations based on the fundamental conservation principles of mass, momentum, energy, and species. These equations are supplemented by additional models that describe radiation, turbulence, and combustion in the furnace. The foregoing set of equations is solved numerically on a computer to obtain predictions of the temperature field in the furnace and the load, composition of the exhaust gas, heat transfer to the load by radiation and convection, and furnace thermal efficiency. The computer program is used to study the effects of various design and operating parameters on the quantities of interest. The model predictions are compared with published test data or operating data on furnaces obtained from industrial firms who have been collaborating with us on the project.

Project Implications: The mathematical models can be used to predict either the natural gas consumption and the thermal efficiency of a given furnace or the design features required to achieve a specified thermal efficiency, temperature distribution, and heating rate. The computer based models can provide this information in a relatively inexpensive and quick manner, enabling the designer to explore a wide range of options for enhancing the performance of the furnace. The models provide insight into the basic heat transfer phenomena, resulting in improved equipment designs. As research tools, the models can eliminate the need for costly experimental tests and greatly assist in the design of new experiments and/or interpretation of test data.

GRI Project Manager
Ferol Fish
Manager, Physics
Physical Sciences Department

OVERALL PROGRAM OBJECTIVES

The overall objectives of the research program are:

1. To obtain improved understanding of radiation and total heat transfer in:
   - i) Indirectly fired industrial furnaces and
   - ii) Directly fired furnaces.
2. To develop mathematical-numerical models to predict radiation and convection heat transfer as well as thermal performance in industrial furnaces.
3. To exercise the models to simulate furnaces and to identify furnace configurations, operating conditions, load positions, etc. which yield more effective heat transfer to the load and a higher overall furnace thermal performance. The research methodology consists of:
   - Critical literature review
   - Mathematical model construction and validation using available test data
   - Parametric calculations using the models developed
   - Identification of heat transfer-thermal performance enhancement schemes.
   - Validation of the models using available test data.

SPECIFIC OBJECTIVES AND WORK TASKS - CURRENT YEAR

The specific objectives and the work tasks for the current year (1993) together with the performance schedule are shown in the accompanying table.

Table 1. Work tasks and performance schedule for 1993.

Work Tasks	Project Month - 1993											
	1	2	3	4	5	6	7	8	9	10	11	12
Indirect Fired Furnaces												
• Two-Dimensional Model for a Straight Through Through Radiant Tube				x	x	x	x	x	x	x		
• Indirect Fired Furnace Systems Models	x	x	x	x	x	x	x	x				
• Validation of Systems Models			x	x	x	x	x	x	x	x		
Direct Fired Furnaces												
• Refinements to Previously Developed Furnace System Model	x	x	x	x	x							
• Validation	x	x	x	x	x	x	x	x	x	x	x	x

NOMENCLATURE

A	area
b	thickness of the load
c	specific heat for a solid
c_p	specific heat at constant pressure
D	diameter
d	thickness, diameter
e	total energy
f	mixture fraction; turbulent model functions
F_{k-j}	configuration factor between k-th and j-th surfaces
H	height of the furnace; total enthalpy
ΔH_f	enthalpy of reaction
h	convective heat transfer coefficient; specific enthalpy
h	effective heat transfer coefficient accounting for radiative and convective heat transfer
I	radiant intensity
J	radiosity at a surface
k	thermal conductivity; turbulent kinetic energy
ℓ	mixing length
L	length, path length
M	number of surface zones
$\dot{m}$	mass flow rate
m_i	mass fraction of species i
N	number of radiant tubes
Pr	Prandtl number
p	pressure or scattering phase function
$p(f)$	probability density function as a function of f
P	perimeter
Q_{net}	net heat transfer into a zone
q	heat flux leaving a surface
r	radial coordinate
R	radius

R_t	turbulent Reynolds number
Re_D	Reynolds number based on diameter
s	number of surface zones in contact with a single gas zone
S	source term
Sc	Schmidt number
t	time
T	temperature
$\overline{\mathscr{F}}$	radiant heat flux vector
U_i	velocity component
V	velocity or volume
w	discrete ordinates model quadrature weighting factor
W	width
x	coordinate direction
y	coordinate direction, as shown in Fig. 2.2; linear distance from radiant tube wall
y^+	dimensionless distance from radiant tube wall
z	axial distance along the radiant tube
α	thermal diffusivity, absorptivity
β	Shvab-Zeldovich coupling parameter
δ	thickness
δ_{kj}	Kronecker delta function: $\delta = 1$ when $k = j$ and $\delta = 0$ when $k \neq j$
ϵ	emissivity or turbulence dissipation rate
ν	kinematic viscosity or frequency
η	furnace efficiency
Γ	diffusion coefficient
τ	shear stress
κ	mean absorption coefficient; fuel burn-up coefficient
λ	wavelength
μ	dynamic viscosity
Ω	solid angle
ϕ	generalized scalar variable
ρ	density
σ	Stefan-Boltzmann constant
σ_ϕ	turbulent Prandtl number for quantity ϕ

Subscripts

a	air
A	air
amb	ambient
b	blackbody
conv	convection
cp	combustion products
DB	Dittus-Boelter
en	enclosure
exh	exhaust
f,fu	fuel
g	gas
i,j,k,ℓ	zone index number
i	inner
init	initial quantity
ℓ	laminar
L	load
m	mass fraction
o	outer
ox	oxidant
rad	radiation
s	surrounding furnace atmosphere or gas zone, surface, or solid
st	stoichiometric
t	radiant tube or turbulent
tot	total
w	furnace wall

CONVERSION FACTORS

Temperature:	$T(^\circ F) = 9/5\ T\ (^\circ C) + 32$
	$T(R) = T\ (^\circ F) + 460$
	$T(K) = T(^\circ C) + 273$
Power:	$1\ kW = 3413\ BTU/hr$
	$1\ hp = 746\ W = 550\ ft\ lb_f/s$
Energy:	$1\ Btu = 1055\ J$
Pressure:	$1\ psi = 6.895\ kPa$
Force:	$1\ lb_f = 4.448\ N$
Mass:	$1\ lb_m = 0.456\ kg$
Distance:	$1\ ft = 0.3096\ m$
Specific heat:	$1\ Btu/lb_m\ R = 1285\ J/kg\ K$

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