Heat exchangers with longitudinal fins for recuperative burners: a combined approach to design involving OpenFOAM and optimization algorithms

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Description of the problem

Object

kilns for the ceramic industry

Considerations

high temperature energy intensive process

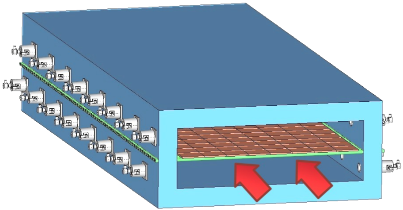
interesting margins for efficiency improvement

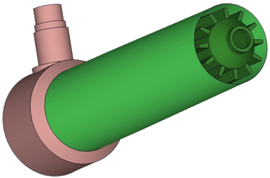
Goal

reduce fuel consumption

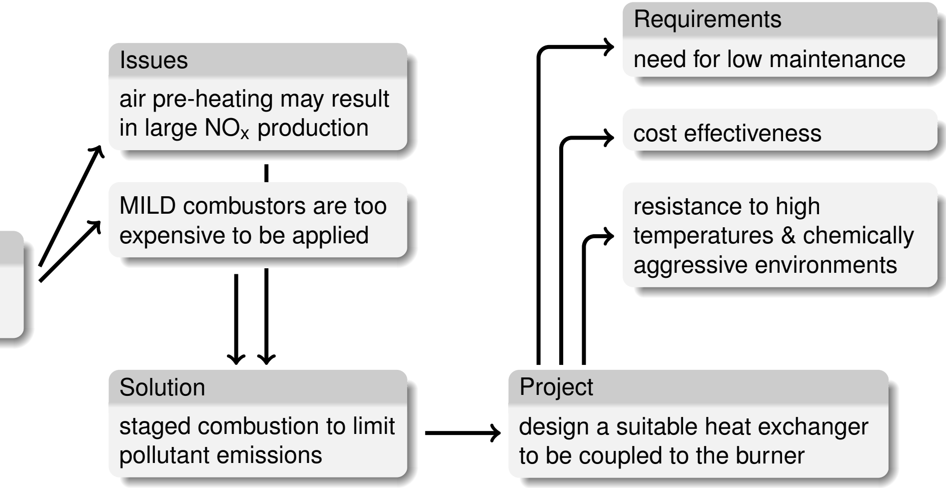
Idea

use recuperative burners to exploit gas enthalpy by pre-heating the combustion air





Description of the problem



Issues

air pre-heating may result in large NO_x production

MILD combustors are too expensive to be applied

Solution

staged combustion to limit pollutant emissions

Project

design a suitable heat exchanger to be coupled to the burner

Requirements

need for low maintenance

cost effectiveness

resistance to high temperatures & chemically aggressive environments

Description of the problem

Exchanger Type Choice

simple, finned, concentric tubes heat exchanger

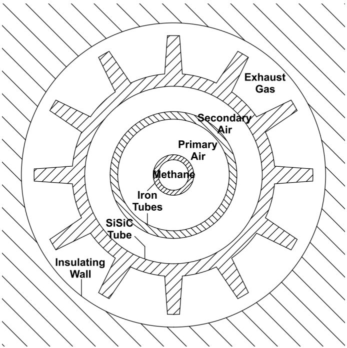
Material Choice

Silicon infiltrated silicon carbide

Design Tools

CFD simulations w/ OpenFOAM 2.3.0

In-house written optimization tool



In-house optimization tool features

Optim v1.02

written in Python

intuitive TUI guides the optimization setup

can be fully operated through scripts

easily linkable to any simulation software through text files . . . including OpenFOAM!

still at the early stages of development, just a few algorithms implemented so far

modularly expandable

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---------------------------------------------------
            OPTIM Text User Interface
   by Marco Cavazzuti - mimesis srl      v 1.02
---------------------------------------------------

MAIN MENU
  1- Create DOE
  2- Setup optimization
  R- Run the optimization
  X- Exit
Please make your choice

1

DOE MENU
  1- Random
  2- Full Factorial
  Q- Go back to main menu
  X- Exit
Please choose the algorithm

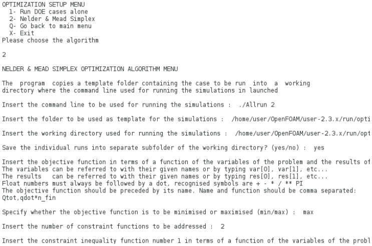
1

RANDOM DOE ALGORITHM MENU
Insert the number of variables :  6

Insert the name and the min to max range for the variable number 1 as comma separated values
(e.g. the input should be in the form varName, minValue, maxValue) :  n_fin,10.0,20.0

Insert the name and the min to max range for the variable number 2 as comma separated values
(e.g. the input should be in the form varName, minValue, maxValue) :  ex_f_rad,45.0,60.0

Insert the name and the min to max range for the variable number 3 as comma separated values
(e.g. the input should be in the form varName, minValue, maxValue) :  eh_gap,2.0,6.0
```



```
OPTIMIZATION SETUP MENU
  1- Run DOE cases alone
  2- Nelder & Mead Simplex
  Q- Go back to main menu
  X- Exit
Please choose the algorithm

2

NELDER & MEAD SIMPLEX OPTIMIZATION ALGORITHM MENU

The  program  copies a template folder containing the case to be run  into  a  working
directory where the command line used for running the simulations in launched

Insert the command line to be used for running the simulations :  ./Allrun 2

Insert the folder to be used as template for the simulations :  /home/user/OpenFOAM/user-2.3.x/run/opti

Insert the working directory used for running the simulations :  /home/user/OpenFOAM/user-2.3.x/run/opt

Save the individual runs into separate subfolder of the working directory? (yes/no) :  yes

Insert the objective function in terms of a function of the variables of the problem and the results of
The variables can be referred to with their given names or by typing var[0], var[1], etc...
The results   can be referred to with their given names or by typing res[0], res[1], etc...
Float numbers must always be followed by a dot, recognised symbols are + - * / ** PI
The objective function should be preceded by its name. Name and function should be comma separated:
Qtot,qdot*n_fin

Specify whether the objective function is to be minimised or maximised (min/max) :  max

Insert the number of constraint functions to be addressed :  2

Insert the constraint inequality function number 1 in terms of a function of the variables of the probl
```

CFD simulations

Geometry

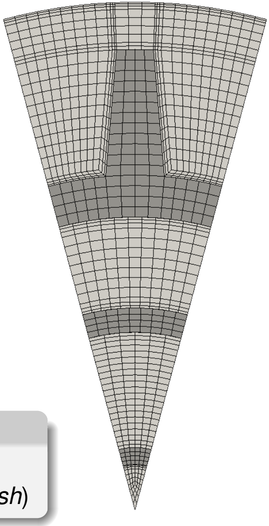
exploiting the symmetry

Solver

chtMultiRegionSimpleFoam
$\approx$ 20 mins. on 4 CPUs for 1 run

Physics

κ-ω SST turbulence model
b.l. w/ $y^+ < 1$ at the wall
P-1 radiation model
Sutherland viscosity
JANAF coeffs. for c_p and h
iron properties: constant
SiSiC properties: linear w/ T
no species/combustion models



Mesh

non-conformal, fully hexahedral (*blockMesh*)

CFD simulations

Operating Conditions

$Q'_{\text{brn}} = 13\,\text{kW}$; $\lambda = 1.2$
70 % secondary air
hp. complete combustion

$\longrightarrow$

Boundary Conditions

$M'_{\text{CH}_4} = 0.25\,\text{g/s}$
$M'_{\text{air},1} = 1.49\,\text{g/s}$
$M'_{\text{air},2} = 3.47\,\text{g/s}$
$M'_{\text{exh}} = 5.21\,\text{g/s}$ (full section)
$\Rightarrow \text{Re}_{\text{CH}_4} \approx \text{Re}_{\text{air},1} \approx \text{Re}_{\text{air},2} \approx$
$\approx 1900 \div 2700$
$\text{Re}_{\text{exh}} \approx 500 \div 1000$
$T_{\text{CH}_4} = T_{\text{air},1} = T_{\text{air},2} = 26\,^{\circ}\text{C}$
$T_{\text{exh}} = 1300\,^{\circ}\text{C}$ (inlet)
adiabatic insulating wall

Optimization

Variables & Ranges

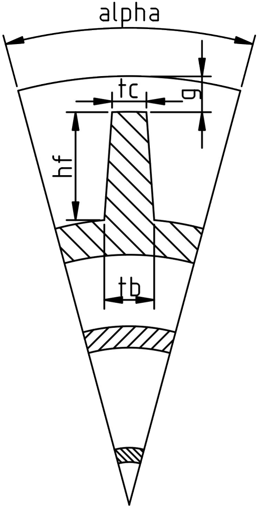
fin number	10 $\leq$	$n_f = \alpha/2\pi$	$\leq$ 20
fin height	5 mm $\leq$	f_h	$\leq$ 20 mm
fin base thick.	5 mm $\leq$	t_b	$\leq$ 8 mm
fin thick. ratio	0.4 $\leq$	$r_f = t_c/t_b$	$\leq$ 0.99
fin crest gap	2 mm $\leq$	g	$\leq$ 6 mm
exch. length	600 mm $\leq$	l_e	$\leq$ 700 mm

Objective

maximize Q'_{exch}

Constraints

$\Delta p_{exh} \leq 2$ mmH$_2$O (performance)
$V_{exch} \leq 1690$ mm^3 (SiSiC cost)



Optimization

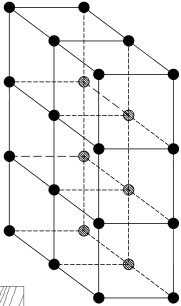
Methods

full factorial
design of experiments
$+$
Nelder & Mead simplex
algorithm

FF-DOE

levels: $n_f \times 4$; $f_h \times 4$; $t_b \times 2$
$r_f \times 2$; $g \times 3$; $l_e \times 4$

design points: 768
simulations: 588
feasible designs: 203



N&M Simplex (not fully converged)

initialization w/ 7 random pts in the design space
design points: 46–53
simulations: 36–38
feasible designs: 28–36

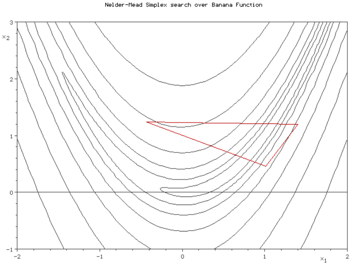


image source: Wikimedia Commons

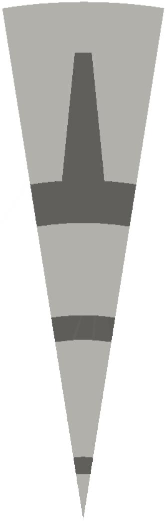
Results

Current Configuration

design: $n_f = 12.0$; $f_h = 15.0$; $t_b = 7.0$
$r_f = 0.63$; $g = 5.6$; $l_e = 640.0$
performance: $Q'_{exch} = 1902.4$ W
constraints:
$\Delta p_{exh} = 2.0$ mmH$_2$O
$V_{exch} = 1690$ mm^3

FF-DOE

best design: $n_f = 20.0$; $f_h = 15.0$; $t_b = 5.0$
$r_f = 0.40$; $g = 6.0$; $l_e = 700.0$
performance: $Q'_{exch} = 2184.4$ W
constraints satisfaction:
$\Delta p_{exh} = 15.9 \text{ Pa} \leq 2.0$ mmH$_2$O
$V_{exch} = 1559.7 \text{ mm}^3 \leq 1690$ mm^3



Results

N&M Simplex (scratch start)

best design: $n_f = 19.8$; $f_h = 16.4$; $t_b = 5.1$
$r_f = 0.47$; $g = 5.2$; $l_e = 668.4$

performance: $Q'_{exch} = 2145.1 \text{ W}$

constraints satisfaction:

$\Delta p_{exh} = 15.7 \text{ Pa} \leq 2.0 \text{ mmH}_2\text{O}$

$V_{exch} = 1602.4 \text{ mm}^3 \leq 1690 \text{ mm}^3$

N&M Simplex (guided start)

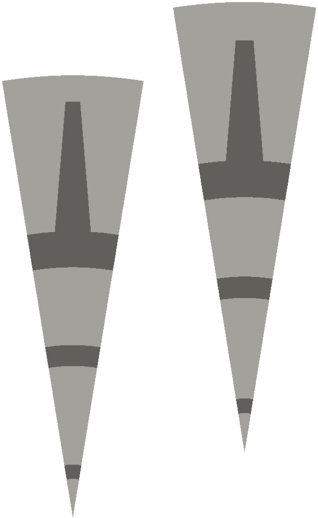
best design: $n_f = 19.6$; $f_h = 18.1$; $t_b = 5.0$
$r_f = 0.41$; $g = 3.7$; $l_e = 697.8$

performance: $Q'_{exch} = 2225.8 \text{ W}$

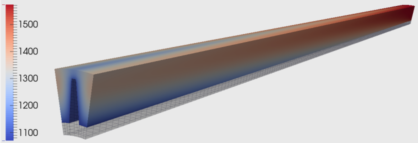
constraints satisfaction:

$\Delta p_{exh} = 16.6 \text{ Pa} \leq 2.0 \text{ mmH}_2\text{O}$

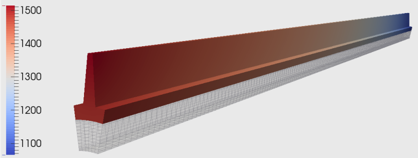
$V_{exch} = 1688 \text{ mm}^3 \leq 1690 \text{ mm}^3$



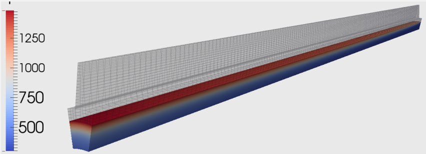
Results



Exhaust Temperature



Exchanger Temperature



Secondary Air Temperature

Conclusions

chtMultiRegionSimpleFoam

used for investigating a concentric pipes finned heat exchanger

OpenFOAM 2.3.0

coupled to a in-house optimization tool

Optimization Tool + OF Scripts

were able to handle meshing, solving, and post-processing automatically

Geometry

the heat exchanger geometry has been parameterized

Objective & Constraints

heat exchange maximized under cost and pressure drop constraints

Nelder & Mead Algorithm

not the best choice for constr. optimization (misconvergence may occur), but it worked fine

Performance

increased by 17 % compared to the initial exchanger design

Conclusions

Thanks

Thank you for your attention!

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References:
M. Cavazzuti, *Optimization Methods: from Theory to Design*, Springer, 2013.
M. Cavazzuti, E. Agnani, M.A. Corticelli *Optimization of a finned concentric pipes heat exchanger for industrial recuperative burners*, Applied Thermal Engineering, Accepted for Publication.