The modelling of particle build up in shell-and-tube heat exchangers due to process cooling water

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by

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Keywords

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Sedimentation

Realizable k-ε

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Single-segmental

Double-segmental

Disc-and-doughnut

Abstract

Sasol Limited experiences extremely high particulate fouling rates inside shell-and-tube heat exchangers that utilize process cooling water. The water and foulants are obtained from various natural and process sources and have irregular fluid properties. The fouling eventually obstructs flow on the shell side of the heat exchanger to such an extent that the tube bundles have to be replaced every nine months. Sasol requested that certain aspects of this issue be addressed.

To better understand the problem, the effects of various tube and baffle configurations on the sedimentation rate in a shell-and-tube heat exchanger were numerically investigated. Single-segmental, double-segmental and disc-and-doughnut baffle configurations, in combination with square and rotated triangular tube configurations, were simulated by using the CFD software package, STAR-CCM+. In total, six configurations were investigated.

The solution methodology was divided into two parts.

Firstly, steady-state solutions of the six configurations were used to identify the best performing model in terms of large areas with high velocity flow. The results identified both single-segmental baffle configurations to have the best performance.

Secondly, transient multiphase simulations were conducted to investigate the sedimentation characteristics of the two single-segmental baffle configurations. It was established that the current state of available technology cannot adequately solve the detailed simulations in a reasonable amount of time and results could only be obtained for a time period of a few seconds.

By simulating the flow fields for various geometries in steady-state conditions, many of the observations and findings of literature were verified. The single-segmental baffle configurations have higher pressure drops than double-segmental and disc-and-doughnut configurations. In similar fashion, the rotated triangular tube configuration has a higher pressure drop than the square arrangement. The single-segmental configurations have on average higher flow velocities and reduced cross-flow mass flow fractions. It was concluded from this study that the single-segmental baffle with rotated triangular tube configuration had the best steady-state performance.

Some results were extracted from the transient multiphase simulations. The transient multiphase flow simulation of the single-segmental baffle configurations showed larger concentrations of stagnant sediment for the rotated triangular tube configuration versus larger concentrations of suspended/flowing sediment in the square tube configuration. This result was offset by the observation that the downstream movement of sediment was quicker for the rotated triangular tube configuration.

No definitive results could be obtained, but from the available results, it can be concluded that the configuration currently implemented at Sasol is best suited to handle sedimentation. This needs to be verified in future studies by using advanced computational resources and experimental results.

Opsomming

Sasol Beperk ervaar uitermatige hoë aanpakkingstempo's binne in buis-en-mantel-hitteruilers wat aanlegverkoelingswater gebruik. Die water en aanpakkings word van verskeie natuurlike en prosesbronne verkry en het afwykende eienskappe. Mettertyd versper die aanpakking die vloei aan die mantelkant van die hitteruiler sodanig dat die buis-bundels elke nege maande vervang moet word. Sasol het versoek dat sekere aspekte van hierdie probleem aangespreek word.

Om die probleem beter te verstaan, is verskeie buis- en sperplaat konfigurasies numeries ondersoek om die effek daarvan op die sedimentasie tempo's binne buis-en-mantel-hitteruilers te bepaal. Enkel segmentale, dubbel segmentale en plaat-en-ring-tipe sperplaat konfigurasies, in kombinasie met vierkantige en geroteerde driehoekige buiskombinasies, is deur middel van die berekeningsvloeimeganika sagteware, STAR-CCM+ gesimuleer. Ses konfigurasies is gesimuleer.

Die oplossingsmetodologie kan in twee dele verdeel word.

Eerstens is 'n gestadigde-toestand-oplossing van die ses konfigurasies gebruik om die model te identifiseer wat die beste in terme van groot areas met hoë vloeisnelhede presteer het. Beide die enkel segmentale sperplaat konfigurasies het die beste resultate gelewer.

Tweedens is tydafhanklike multifase simulasies uitgevoer om die sedimentasie karakteristieke van albei die enkel segmentale sperplaat konfigurasies te ondersoek. Daar is bevind dat die tegnologie wat tans beskikbaar is nie geskik is om die gedetaileerde simulasies binne 'n redelike tyd op te los nie. Slegs 'n paar sekondes in reële tyd kon gesimuleer word.

Deur die vloeivelde van verskeie geometrieë in gestadigde-toestand kondisies te simuleer, is baie van die waarnemings en bevindinge in die literatuur studie bevestig. Die enkel segmentale sperplaat konfigurasies het 'n hoër drukval as die dubbel segmentale en plaat-en-ring-tipe konfigurasies gehad. Terselfdetyd, het die geroteerde driehoekige buis konfigurasie 'n hoër drukval as die vierkantige buis konfigurasie gehad. Die enkel segmentale konfigurasies het hoër gemiddelde vloeisnelhede en verlaagde kruisvloei massavloei fraksies gehad. Hieruit kan die gevolgtrekking gemaak word dat die enkel segmentale sperplaat met geroteerde driehoekige buis konfigurasie die beste gestadigde-toestand prestasie getoon het.

Enkele resultate kon wel uit die tydafhanklike multifase simulasies waargeneem word. Die tydafhanklike multifase simulering van die enkel segmentale konfigurasies het groter konsentrasies van stagnante sediment in die geroteerde driehoekige buis konfigurasie getoon, teenoor groter konsentrasies van gesuspendeerde sediment in die vierkantige buis konfigurasie. Hierdie resultaat is egter weerspreek deur die waarneming dat die sediment in die geroteerde driehoekige buis konfigurasie vinniger stroomaf beweeg het.

Alhoewel geen spesifieke resultate verkry kon word nie, kan daar tog bevind word dat die konfigurasie wat tans by Sasol gebruik word die beste geskik is om die sedimentasie tempo te vertraag. Hierdie bevinding moet egter in toekomstige navorsing met behulp van gevorderde rekenaarhulpbronne en eksperimentele resultate geverifieer word.

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List of abbreviations

ALE	Arbitrary Lagrangian-Eulerian
ASME	American Society of Mechanical Engineers
BFS	Backward-facing step
CFD	Computational fluid dynamics
CMSP	Compact multiple shell pass
DDR	Destination data register
DES	Direct eddy simulation
DNS	Direct numerical simulation
GB	Gigabyte
GGDH	General gradient diffusion hypothesis
GHz	Gigahertz
HPC	High-performance computer
HTRI	Heat Transfer Research Institute
LES	Large eddy simulation
LHS	Left-hand side
MHz	Megahertz
PIV	Particle image velocimetry
RAM	Random access memory
RANS	Reynolds-averaged Navier-Stokes
RHS	Right-hand side
RNG	Renormalization group
RSM	Reynolds stress model
SGDH	Simple gradient-diffusion hypothesis
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations
SST	Shear stress transport
STHE	Shell-and-tube heat exchangers
TEMA	Tubular Exchangers Manufacturers Association
TVD	Total variation diminishing
VOF	Volume of fluid

Nomenclature

Variable	Definition	Variable	Definition
A	Area	$C_{\varepsilon 1}$	K-ε model coefficient
a	Acceleration	$C_{\varepsilon 2}$	K-ε model coefficient
$\boldsymbol{A}$	Area vector	$C_{\varepsilon 3}$	Buoyancy production of dissipation
A_0	Constant	C_μ	Model coefficient for turbulent viscosity
A_{bl}	Blending function width parameter	C_v	Wolfstein model coefficient
A_ij^D	Linearized Drag coefficient	d_a	Tube outer diameter
A_s	Coefficient for viscosity relation	d_g	Hydraulic diameter
A_sc	Interior cross flow section area at or near shell center line	D_i	Shell inside diameter
A_sp	Solid pressure force model constant	dx	Differential element length in x direction
A_wz	Window zone cross flow area excluding tubes	dy	Differential element length in y direction
a_x	Acceleration in Cartesian X direction	dz	Differential element length in z direction
A_ε	Wolfstein model coefficient	E	Energy
A_μ	Wolfstein model coefficient	e	Minimum distance between tube surfaces
B	Wall law constant for blended function	E'	Log law coefficient
B_s	Baffle spacing	E_ll	Log law constant
B_se	Baffle spacing in end sections	f	Elliptic relaxation function
c	Speed of sound	f	Friction factor
C	Wall law constant for blended function	f_b	Bundle bypass correction factor
C_D	Standard drag coefficient	$\boldsymbol{F}_\mathrm{ij}$	Force per cell volume that phase j exerts on phase i
C_L	Lift coefficient	$\boldsymbol{F}_\mathrm{ij}^\mathrm{D}$	Drag force on phase i due to phase j
c_l	Wolfstein two-layer model coefficient	$\boldsymbol{F}_\mathrm{ij}^\mathrm{L}$	Lift force on phase i due to phase j
C_m	Compressibility modification constant	$\boldsymbol{F}_\mathrm{ij}^\mathrm{TD}$	Turbulent dispersion force of phase i due to phase j
C_VM	Virtual mass force coefficient	$\boldsymbol{F}_\mathrm{ij}^\mathrm{VM}$	Virtual mass force of phase i due to phase j

f_r	Roughness function
f_s	End correction factor for unequal baffle spacing
$(\boldsymbol{F}_{Solid})_i$	Solid pressure force on phase i
$\vec{\boldsymbol{F}}^b$	Body Force
$\boldsymbol{F}_x$	Force in Cartesian X direction
$\boldsymbol{F}_x^b$	Body Force in Cartesian X direction
$\boldsymbol{F}_y^b$	Body Force in Cartesian Y direction
$\boldsymbol{F}_z^b$	Body Force in Cartesian Z direction
f_z	Viscosity correction factor
$f_{z,l}$	Viscosity correction factor for laminar flow
$f_{z,t}$	Viscosity correction factor for turbulent flow
$\boldsymbol{g}$	Gravity vector
G_b	Turbulent production due to buoyancy
G_k	Turbulent production
H	Baffle cut
i	1st direction index of a three-dimensional coordinate system
l	Distance between the internal tube sheet surfaces
l_{cd}	Interaction length scale between phases
l_ε	Length scale function
j	2nd direction index of a three-dimensional coordinate system
k	Turbulent kinetic energy
k_p	Pressure drop coefficient
m	Mass
M_{ij}	Inter phase momentum transfer per unit volume
n	Hindered settling exponent
N	Number of computational cells
N_b	Number of baffles
N_c	Number of cross flow tube rows
n_p	Number of particle phases
N_w	Number of tube rows in window section
P	Pressure
Pr	Prandtl number
p_t	Tube pitch
q_1	1st coordinate of three dimensional coordinate system
q_2	2nd coordinate of three dimensional coordinate system
q_3	3rd coordinate of three dimensional coordinate system
r	Equivalent sand grain roughness
$\vec{r}$	Vector field
R^+	Roughness parameter
R_1	Roughness function constant
R_2	Roughness function constant
R_3	Roughness function constant
R_B	Bypass flow area ratio
Re	Reynolds number
Re_y	Turbulent Reynolds number
$Re_y{*}$	Two-layer applicability limit
s	Entropy
S	Modulus of the mean strain rate tensor
S_{ij}	Mean strain rate of i due to j

S_{jk}	Mean strain rate of j due to k
S_k	Turbulent kinetic energy source term
S_{ki}	Mean strain rate of k due to i
S_ε	Turbulent dissipation rate source term
t	Time
T	Temperature
u	Velocity in Cartesian X direction
$U(*)$	Turbulent viscosity model coefficient
u^*	Reference velocity used in wall functions
u^+	Non-dimensional wall parallel velocity
$\mathbf{u}_b$	Velocity component perpendicular to **g**
$u`_i u`_i$	Normal Reynolds stress
u_p	Component of wall cell velocity parallel to the wall
u_{sc}	Cross flow velocity
u_{wz}	Window zone cross flow velocity
V	Volume
v	Velocity in Cartesian Y direction
$\vec{\mathbf{V}}$	Velocity vector
$\mathbf{v}_f$	Velocity of fluid
$\mathbf{v}_b$	Velocity component parallel to **g**
v_g	Grid velocity
$\mathbf{v}_i$	Velocity of phase i
$\mathbf{v}_j$	Velocity of phase j
$\mathbf{v}_r$	Relative velocity
$\mathbf{W}$	Rotation rate tensor
w	Velocity in the Cartesian Z direction
w_n	Nozzle velocity
w_z	Characteristic velocity
x	Cartesian x direction
y	Cartesian y direction
y^+	Non-dimensional wall distance
y_m^+	Layer intersectional value for the non-dimensional wall distance
y_n	Normal distance from the wall to cell centroid
z	Cartesian z direction
α_c	Volume fraction of continuous phase
α_d	Volume fraction of discrete phase
α_i	Volume fraction of phase i
α_j	Volume fraction of phase j
$\alpha_{p,i}$	Cell packing limit
$\alpha_{p,max}$	Maximum cell packing limit
α_{tr}	Transition volume fraction
β	Volumetric coefficient of thermal expansion
γ	Intensive property
ΔP	Total Pressure drop
ΔP_b	Pressure drop due to stream line curvature
ΔP_c	Cross flow pressure drop

$\Delta P_{c,0}$	Interior cross flow pressure drop, for ideal tube bank, excluding leakage
ΔP_{cdn}	Converging diverging nozzle pressure drop
ΔP_{ec}	End cross flow pressure drop
$\Delta P_{ec,0}$	End cross flow pressure drop, for ideal tube bank, excluding bypass
ΔP_{n}	Inlet and outlet nozzle pressure drop
ΔP_{wz}	Window section pressure drop
$\Delta P_{wz,l}$	Window section pressure drop for laminar flow
$\Delta P_{wz,t}$	Window section pressure drop for turbulent flow
ΔRe_{y}	Two-layer model constant
ε	Turbulent dissipation rate
ε_0	Ambient turbulence value in source terms counteracting decay
ζ	Realizable k-epsilon model coefficient
θ	Flow inclination angle
κ	Von Karaman constant
λ	Extensive property
μ	Dynamic viscosity
μ_b	Bulk viscosity
μ_c	Dynamic viscosity of continuous phase
μ_m	Molecular viscosity
μ^s	Viscosity of fluid at bulk fluid temperature
μ_{sw}	Viscosity of fluid at wall temperature
μ_t	Turbulent viscosity
ν	Kinematic viscosity
ν_c^t	Continuous phase turbulent kinematic viscosity
ξ_n	Pressure drop coefficients
π	Pi
ρ	Density
ρ_C	Density of continuous phase
ρ_i	Density of phase
σ_k	Schmidt number for turbulent kinetic energy
σ_t	Turbulent Prandtl number
σ_ε	Schmidt number for turbulent dissipation rate
τ	Shear stress
τ_i^m	Molecular shear stress
τ_i^t	Turbulent shear stress
τ_{xx}	Normal stress over area dydz
τ_{yx}	Shear stress over area dxdy
τ_{zx}	Shear stress over area dxdz
υ	Velocity magnitude
Υ_M	Dilation dissipation
Φ	Coefficient for equating viscosity
ψ	Blending parameter
ω	Specific dissipation rate