

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

Shell-and-tube heat exchanger

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Realizable k- ϵ

Multiphase

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 buisbundels 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 berekeningsvloeiemechanika 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 gelever.

Tweedens is tydafhanklike multifase simulaties 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 gedetailleerde simulaties binne 'n redelike tyd op te los nie. Slegs 'n paar sekondes in reële tyd kon gesimuleer word.

Deur die vloeiveld 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 simulaties 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 verlaag. 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	$C_{\epsilon 1}$	K- ϵ model coefficient
a	Acceleration	$C_{\epsilon 2}$	K- ϵ model coefficient
\mathbf{A}	Area vector	$C_{\epsilon 3}$	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	\mathbf{F}_{ij}	Force per cell volume that phase j exerts on phase i
C_L	Lift coefficient	\mathbf{F}_{ij}^D	Drag force on phase i due to phase j
c_l	Wolfstein two-layer model coefficient	\mathbf{F}_{ij}^L	Lift force on phase i due to phase j
C_m	Compressibility modification constant	\mathbf{F}_{ij}^{TD}	Turbulent dispersion force of phase i due to phase j
C_{VM}	Virtual mass force coefficient	\mathbf{F}_{ij}^{VM}	Virtual mass force of phase i due to phase j

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

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

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