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Summary

# Prediction of flow-induced vibration in shell-and-tube heat exchangers

by

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## **Prediction of flow-induced vibration in shell-and-tube heat exchangers**

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### **Summary**

Flow-induced vibration can cause premature tube failure in shell-and-tube heat exchangers and is therefore incorporated in the heat exchanger design, together with the heat transfer and pressure drop, as a primary concern. In this study three methods for the prediction of flow-induced vibration were investigated. The results of the three methods were compared with each other and with experimental data. For comparison purposes vibration measurements were taken on a Tail gas shell-and-tube heat exchanger at Sasol Synthetic Fuels (SSF).

Firstly, software developed by the Heat Transfer Research Institute (HTRI) was used to predict flow-induced vibration in the Tail gas shell-and-tube heat exchanger. The HTRI analyses calculated excitation frequencies due to vortex shedding, turbulence buffeting, fluid-elastic instability and acoustic resonance. These excitation frequencies were then compared to the lowest HTRI calculated natural frequency of the tubes (using a 20 percent margin of uncertainty) to predict whether vibration would occur. Additional natural frequency calculations were made to determine higher natural frequencies of the tubes, using equations from the Tubular Exchanger Manufacturers Association (TEMA) standards. Finite Element Methods (FEM) were used to determine the effect that the support configurations have on the tubes' natural frequencies.

Secondly, Computational Fluid Dynamic (CFD) analyses were used to simulate the flow velocities and pressure drops through the heat exchanger. These results were

compared with the HTRI predicted average cross-flow velocity and pressure drop values.

Thirdly, vibration measurements were recorded on the Tail gas heat exchanger using Siglab 20-42 data acquisition equipment. Vibration on the heat exchanger shell was measured using strain gauges as well as 500 mV/g and 100 mV/g accelerometers. Support vibration measurements were recorded using 2 V/g accelerometers.

The CFD analyses predicted that vibration (for a specific excitation frequency) would occur over a range of mass flow rates, while the HTRI analyses only predicted vibration at a single mass flow rate. The experimental results confirmed that vibration did occur at the HTRI predicted natural frequency, but also over a range of other mass flow rates, as predicted by the CFD analyses.

*Keywords:* Flow-induced vibration, vortex shedding, turbulence buffeting, fluid-elastic instability, shell-and-tube heat exchanger, tube vibration, tubes in cross-flow, Computational Fluid Dynamic (CFD) analysis, Finite Element Methods (FEM), Heat Transfer Research Institute (HTRI) analysis.

## Voorspelling van vloei-geïnduseerde vibrasie in dop-en-buis hitteruilers

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### Opsomming

Vloei-geïnduseerde vibrasie in dop-en-buis hitteruilers kan veroorsaak dat die buise voor hul verwagte ontwerp-leeftyd faal. Dit is dus noodsaaklik om vibrasie analises in te sluit by die ontwerp van hitteruilers, tesame met warmteoordrag en drukval as primêre oorwegings. In hierdie studie word drie metodes vir die voorspelling van vloei-geïnduseerde vibrasie ondersoek, onderling vergelyk, en ook met eksperimentele waarnemings vergelyk. Vir hierdie doel is 'n afvoer gas dop-en-buis hitteruiler by Sasol Sintetiese Brandstowwe (SSF) gebruik.

Eerstens is daar van sagteware, wat deur die *Heat Transfer Research Institute* (HTRI) versprei word, gebruik gemaak om vloei-geïnduseerde vibrasie in die hitteruiler te voorspel. Die HTRI analises bereken die opwekkingsfrekwensies as gevolg van vorteks afgooiing, turbulente opwekking, vloei-elastiese onstabieleit en akoestiese resonansie. Die opwekkingsfrekwensies word dan met die laagste HTRI berekende natuurlike frekwensie van die buise vergelyk (deur van 'n 20 persent onsekerheidsband gebruik te maak) om te bepaal of die buise gaan vibreer. Addisionele natuurlike frekwensies, hoër as die HTRI natuurlike frekwensie van die buise, is bereken met behulp van die *Tubular Exchanger Manufacturers Association* (TEMA) standaard. Eindige element metodes is gebruik om die effek wat die buis ondersteuning op die natuurlike frekwensies van die buise het, te bepaal.

Tweedens is berekenings vloeï-dinamika (CFD) analyses gebruik om die vloeïsnelhede en drukval deur die hitteruiler te simuleer. Hierdie resultate is met die HTRI analyses se gemiddelde dwarsvloeï snelhede en drukvalle vergelyk.

Derdens is vibrasïemetinge op die afvoer gas hitteruiler geneem deur van die Siglab 20-42 dataverwerker gebruik te maak. Vibrasïe op die dop van die hitteruiler is met behulp van rekstrokies, sowel as 500 mV/g en 100 mV/g versnellingsmeters gemeet. Die voetstukvibrasïe van die hitteruiler is met 2 V/g versnellingsmeters gemeet.

Die CFD analyses het voorspel dat vibrasïe (vir 'n spesifieke opwekkingsfrekwensie) sal voorkom oor 'n band van massavloeïtempo's, terwyl die HTRI analyses vibrasïe slegs by 'n enkele massavloeïtempo voorspel het. Die eksperimentele resultate bevestig dat vibrasïe wel by die HTRI voorspelde frekwensie voorkom, maar ook oor 'n band van massavloeïtempo's, soos die CFD analyses voorspel het.

*Sleutelwoorde:* Vloeï-geïnduseerde vibrasïe, vorteks afgooïing, turbulente opwekking, Vloeï-elastiese onstabiliteit, dop-en-buis hitteruilers, buis vibrasïe, buise in dwarsvloeï, berekenings vloeï dinamika analyses, eindige element metodes, *Heat Transfer Research Institute* (HTRI) analyses.

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**Nomenclature**

A	Area	$m^2$
$A_f$	Fin surface area	$m^2$
$A_g$	Gap Area	$m^2$
$A_p$	Prime (unfinned) area	$m^2$
a	Amplitude	m
C	Fluid force coefficient	
$C_D$	Drag coefficient	
$C'_D$	Fluctuating drag coefficient	
$C_L$	Lift coefficient	
$C'_L$	Fluctuating lift coefficient	
$C_n$	Frequency constant	
$C_u$	U-tube frequency constant	
$c_r$	Critical velocity	m/s
d	Characteristic length	m
$d_o$	Tube outside diameter	in
D	Diameter	m
$D_i$	Tube inside diameter	m
$D_o$	Tube outside diameter	m
E	Modulus of elasticity	$N/m^2$
F	Force	N
f	Friction factor	
$f_a$	Acoustic frequency	Hz
$f_n$	Natural frequency	Hz
$f_{ns}$	Stressed tube natural frequency	Hz
$f_{nu}$	U-tube natural frequency	Hz
$f_s$	Acoustic shedding frequency	Hz
$f_{tb}$	Turbulent buffeting frequency	Hz
$f_{tba}$	Acoustic turbulence buffeting frequency	Hz
$f_{vs}$	Vortex shedding frequency	Hz
$f_{vsa}$	Acoustic vortex shedding frequency	Hz
g	Fluctuating forces in the x-direction	N
h	Height	m
h'	Fluctuating forces in the y-direction	N
I	Second moment of area	$m^4$
K	Turbulence kinetic energy	$m^2/s^2$
	Stiffness	N/m
$K_{gv}$	Gate value loss coefficient	
$K_t$	Total loss coefficient	

$k$	Added mass coefficient	
$L$	Length	m
$L_{\text{mid}}$	Mid-span length	m
$l$	Effective flow length	m
$l_n$	Length associated with $n^{\text{th}}$ mode shape	m
$M_e$	Effective mass per unit length	kg/m
$M_m$	Material mass per unit length	kg/m
$M_s$	Virtual mass per unit length of shell-side fluid displaced by the tube	kg/m
$M_t$	Mass per unit length of the fluid inside the tube	kg/m
$\dot{m}$	Mass flow rate	kg/s
$m_n$	Effective mass per unit length of the $n^{\text{th}}$ mode	kg/m
$N$	Number of spans	
$P$	Perimeter	m
	Pressure	Pa
	Tube pitch	m
$P_a$	Axial load	N
$\Delta P$	Pressure drop	Pa
$p_l$	Longitudinal tube pitch	m
$p_t$	Transverse tube pitch	m
$q$	Distributed load	N/m
$R$	U-tube bend radius	m
	Particular gas constant	kNm/kmolK
$\bar{R}$	Universal gas constant	kNm/kmolK
$Re$	Reynolds number	
$r$	Radius	m
$S_a$	Acoustic Strouhal number	
$S_r$	Strouhal number	
$t_b$	Baffle plate thickness	in
$U_g$	Cross flow velocity in gaps	m/s
$u$	Velocity in x-direction	m/s
$u_c$	Cross flow velocity	m/s
$u_\infty$	Free stream velocity	m/s
$V$	Volume	$\text{m}^3$
$v$	Velocity in y-direction	m/s
$w_o$	Effective weight per unit length	lb
$X_p$	Pitch to diameter ratio	
$y^+$	Wall plus value	

**Greek symbols**

$\bar{\alpha}$	Added mass matrix	
$\bar{\alpha}'$	Damping matrix	
$\bar{\alpha}''$	Stiffness matrix	
$\bar{\beta}$	Added mass matrix	
$\bar{\beta}'$	Damping matrix	
$\bar{\beta}''$	Stiffness matrix	
$\delta$	Logarithmic damping	
$\delta_b$	Tip deflection	m
$\varepsilon$	Roughness	m
	Strain	
	Turbulent dissipation	
$\Phi$	Mode shape	
$\Phi_D$	Drag force phase angle	rad
$\Phi_L$	Lift force phase angle	rad
$\kappa$	Curvature	m
$\lambda$	Ratio of end zone span length to central span length	m
$\mu$	Viscosity	Pas
$\rho$	Mass density	kg/m <sup>3</sup>
$\rho_o$	Reference fluid density	lb/in <sup>3</sup>
$\rho_s$	Mass density of shell-side fluid	kg/m <sup>3</sup>
$\bar{\sigma}$	Added mass matrix	
$\bar{\sigma}'$	Damping matrix	
$\bar{\sigma}''$	Stiffness matrix	
$\Omega_D$	Drag force circular frequency	rad/s
$\Omega_L$	Lift force circular frequency	rad/s
$\bar{\tau}$	Added mass matrix	
$\bar{\tau}'$	Damping matrix	
$\bar{\tau}''$	Stiffness matrix	
$\xi$	Damping ratio	
$\xi_n$	Damping ratio of the n <sup>th</sup> mode	

**Abbreviations**

CFD	Computational Fluid Dynamics
FEI	Fluid-Elastic Instability

FEA	Finite Element Analysis
HEDH	Heat Exchanger Design Handbook
HTFS	Heat Transfer and Fluid flow Services
HTRI	Heat Transfer Research Institute
PSD	Power Spectral Density
SSF	Sasol Synthetic Fuels
TEMA	Tubular Exchangers Manufacturing Association

### Heat exchanger classifications according to TEMA

BEM	Bonnet, One Pass Shell, Fixed Tubesheet
AKL	Channel, Two Pass Shell, Fixed Tubesheet
CEU	Channel Integral with Tubesheet, One Pass Shell, U-Tube Bundle
CEN	Channel Integral with Tubesheet, One Pass Shell, Fixed Tubesheet
R	Petroleum and related processing applications