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

by

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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 acquisitioning 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

deur

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Opsomming

Vloei-geïnduseerde vibrasie in dop-en-buis hitteruilers kan veroorsaak dat die buise voor hul verwagte ontwerpleeftyd 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 onstabiliteit 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) standaarde. 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 vloei-dinamika (CFD) analises gebruik om die vloeisnelhede en drukval deur die hitteruiler te simuleer. Hierdie resultate is met die HTRI analises se gemiddelde dwarsvloei snelhede en drukvalle vergelyk.

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

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

Sleutelwoorde: Vloei-geïnduseerde vibrasie, vorteks afgooiing, turbulente opwekking , Vloei-elastiese onstabiliteit, dop-en-buis hitteruilers, buis vibrasie, buise in dwarsvloei, berekenings vloei dinamika analises, eindige element metodes, *Heat Transfer Research Institute* (HTRI) analises.

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Table of contents

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_{mid}	Mid-span length	m
l	Effective flow length	m
l_n	Length associated with nth 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 nth mode	kg/m
N	Number of spans	
P	Perimeter	m
	Pressure	Pa
	Tube pitch	m
P_a	Axial load	N
ΔP	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	
Sr	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_∞	Free stream velocity	m/s
V	Volume	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	
δ	Logarithmic damping	
δ_b	Tip deflection	m
ε	Roughness	m
	Strain	
	Turbulent dissipation	
Φ	Mode shape	
Φ_D	Drag force phase angle	rad
Φ_L	Lift force phase angle	rad
κ	Curvature	m
λ	Ratio of end zone span length to central span length	m
μ	Viscosity	Pas
ρ	Mass density	kg/m^3
ρ_o	Reference fluid density	lb/in^3
ρ_s	Mass density of shell-side fluid	kg/m^3
$\bar{\sigma}$	Added mass matrix	
$\bar{\sigma}'$	Damping matrix	
$\bar{\sigma}''$	Stiffness matrix	
Ω_D	Drag force circular frequency	rad/s
Ω_L	Lift force circular frequency	rad/s
$\bar{\tau}$	Added mass matrix	
$\bar{\tau}'$	Damping matrix	
$\bar{\tau}''$	Stiffness matrix	
ξ	Damping ratio	
ξ_n	Damping ratio of the nth 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