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THE VERTICAL FLOW CENTRIFUGAL GAS-LIQUID SEPARATOR
AND ITS APPLICATION TO THE REMOVAL OF GASES
FROM GEOTHERMAL WELLS

A Thesis submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy in Mechanical Engineering of the School of Engineering of the University of Auckland, New Zealand.

J F G KANYUA
1985
ABSTRACT

Two vertical flow centrifugal gas-liquid separators were designed, built and tested using steam-water and air-water mixtures as the two-phase fluids. The theoretical analysis of the vertical flow centrifugal gas-liquid separator and the experimental data from the model separators is given in this report.

It has been shown that the performance of the vertical flow centrifugal separator is determined by the inlet mass flow rate, vapour-phase mass fraction and the dimensions of the separator components. The important dimensions influencing the performance of the separator have been shown to be the gastube diameter, the gastube inlet diameter and the design of the vortex generator. Large gastube diameters have been shown to give high separation efficiencies. Sharp vortex generator blade exit angles have been shown to give the best performance especially with slugging inlet flow which occurs at relatively low vapour mass fractions. The distance between the vortex generator and the gastube inlet has been shown to have little effect on the separation efficiency. Improvements in the design of the vortex generator, especially the curvature of the blades and the diameter of the hub have been shown to increase both the mass flow capacity and separation efficiency, and to reduce the overall pressure drop which mainly occurs across the vortex generator. The amount of flashing caused by the vortex generator has been shown to be small. The effects of the various parameters on the separation efficiency are discussed in this report.

The vertical flow centrifugal separator has been shown to be capable of liquid separation efficiencies close to one over a wide range of inlet flow conditions. Vapour separation efficiencies in excess of 90% have been shown to be possible and higher efficiencies may be obtained when the dimensions of the separator are optimised.

The application of the vertical flow centrifugal separator to the removal of gases from geothermal wells has been inves-
tigated. A method of estimating the onset of two-phase flow in a geothermal well and hence the location of a separator has been presented. Methods for calculating the pressure drops between the separator and the wellhead have been presented. Sample calculations illustrating the effect of reservoir properties, fluid chemistry and well casing program on pressure drops have also been presented. A general discussion on vertical two-phase flow is given as a background for these calculations. The theory of vapour-liquid equilibria, and the properties of the main components of geothermal fluids have been included as appendices.

The available literature on other methods of gas removal is reviewed and a preliminary comparison of some of these other methods and the downhole separator is also presented. Recommendations for future work and other uses of the vertical flow centrifugal separator are given at the end of this report.
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NOTATION

A  Area
A  Gas distribution coefficient defined in Appendix 1
A' Gas distribution coefficient defined in Appendix 1
A  Constants in Appendix 1, 2 and 3
a  Activity of a solution
a  Dimension defined in Figure 4.6
a  Constant in Equation 3a Appendix 2

B  Constants in Appendices 2 and 3
B  Variable defined in Equation 2.2
b  Constant

C  Constants in text
C_{GV}  Ratio of mass of gas to mass of steam in a mixture
C'_{GV} Ratio of moles of gas to moles of steam in a mixture
C_{GL}  Ratio of mass of gas to mass of brine in a solution
C'_{GL} Ratio of moles of gas to moles of brine in a solution
C_{GT}  Ratio of total mass of gas to total brine in system
C_{SL}  Ratio of NaCl to water in liquid-phase
C_{ST}  Ratio of NaCl to water (substance)
C_{P}  Specific heat at constant pressure
C_{V}  Specific heat at constant volume

D  Constants in Appendix 3
D  Diameter (general)
D  Gas distribution coefficient defined in Appendix 1
D_{bm} Diameter of gastube inlet
D_{C}  Diameter of vapour core
D_{gt} Diameter of gastube
\( D_i \)  Inside diameter of tube  
\( D_o \)  Outside diameter of tube  
\( d_b \)  Diameter of vapour bubble  

E  Constants in Appendix 3  

F  Constants in Appendix 3  
\( F_c \)  Centrifugal force  
\( F_{cg} \)  Ratio \( F_c/F_g \): g-value  
\( F_g \)  Gravity force  
\( F_P \)  Pressure force  
\( F_v \)  Viscous friction force  
\( f \)  fugacity  
\( f \)  Friction factor  
\( f(\cdot) \)  Function of \( z \) or \( r \)  

G  Gibbs function  

G  Mass flux  
\( g \)  Acceleration of gravity  

H  Total enthalpy  
\( h \)  Specific enthalpy  
\( \Delta h^S \)  Enthalpy of solution of a gas  
\( \Delta h_s \)  Enthalpy of mixing of \( \text{NaCl-H}_2\text{O} \) solution  
\( h \)  Pressure drop across orifice plate  

i  polynomial index  

J  Productivity index
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<tr>
<td>$K_h$</td>
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<td>$K_r$</td>
<td>Sink or source strength</td>
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<td>$K_s$</td>
<td>Slip ratio: ratio of gas to liquid velocities</td>
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<td>$K_{ts}$, $K_{sb}$</td>
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<tr>
<td>Q</td>
<td>Total heat transfer rate</td>
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<td>q, q'</td>
<td>Heat transfer rate per unit mass flow rate</td>
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<td>$R_0$</td>
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<td>R</td>
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<td>R</td>
<td>Holdup, void fraction</td>
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\textbf{R}  ~ Radius
\textbf{r}  ~ radius
\textbf{r}^*  ~ Change-over point from free vortex to solid body rotation
\textbf{r}  ~ relative volatility

\textbf{S}  ~ Entropy  
\textbf{S}  ~ Tube perimeter  
\textbf{S}  ~ Parameter defined in Equation 4.16  
\textbf{s}  ~ Entropy

\textbf{T}  ~ Temperature  
\textbf{T}_c  ~ Critical temperature  
\textbf{t}  ~ Time

\textbf{U}  ~ Velocity  
\textbf{U}_c  ~ Velocity of the vapour core  
\textbf{U}_{rc}  ~ U_c \text{ at core-annulus interface } (r = r_c)  
\textbf{U}_{La}  ~ Velocity of liquid film in annular flow  
\textbf{U}_l  ~ Velocity of liquid-phase  
\textbf{U}_G  ~ Velocity of vapour-phase  
\textbf{U}_{GS}  ~ Superficial velocity of vapour-phase  
\textbf{U}_{LS}  ~ Superficial velocity of liquid-phase  
\textbf{U}_t  ~ Tangential velocity component  
\textbf{U}_r  ~ Radial velocity component  
\textbf{U}_z  ~ Axial velocity component  
\textbf{U}_h  ~ Overall heat transfer coefficient  
\textbf{u}  ~ Internal energy

\textbf{V}  ~ volume, volume flow rate  
\textbf{v}  ~ Specific volume
Shaft work
Work output
Work output per unit mass

Mass fraction
Mole fraction
Modified pressure defined in Chapter 4

Dryness
Mass or mole fraction of i in vapour-phase
Fraction of total gas released from solution

Axial distance or elevation
Compressibility factor
Separation zone boundary defined in Chapter 2
Bubble point location relative to wellbottom
Wellbottom elevation
Greek Alphabet

\[ \alpha \] Phase flow area
\[ \alpha \] Thermal diffusivity
\[ \sigma \] Variable defined in Appendix 2
\[ \beta \] Bunsen gas distribution coefficient
\[ \beta \] Distribution of variable B per unit mass in Chapter 2
\[ \delta \] Annular film thickness
\[ \varepsilon \] Tube wall roughness
\[ \varepsilon_c \] Condenser performance factor defined in Chapter 6
\[ \gamma \] Activity coefficient
\[ \gamma \] Constant in Appendix 2
\[ \gamma \] Ratio of specific heats as constant pressure and volume
\[ \lambda \] Friction factor
\[ \lambda \] Ostwald gas distribution coefficient
\[ \mu \] Dynamic or absolute viscosity
\[ \nu \] Kinematic viscosity
\[ \rho \] Density of fluid
\[ \sigma \] Surface tension force
\[ \tau \] Viscous shear stress
\[ \eta \] Efficiency
\[ \psi \] Effective diameter coefficient defined in Chapter 4
\[ \omega \] Absolute humidity
\[ \theta \] Angle or angular coordinate
\[ \phi \] Angle
\[ \phi \] Apparent specific volume of NaCl in solution in Appendix 3
\[ \phi \] Fugacity coefficient
**Subscripts**

A, a  Acceleration term
a  Annulus, annular flow regime
a  Air

b  Brine property
b  Bubble, bubble flow regime
bm  Gastube inlet
bp  Bubble point
bh  Well bottom
bl  Outer edge of boundary layer
c  Core fluid
c  Critical point
c  Centrifugal
cg  Ratio of centrifugal to gravity

f  Froth flow regime
f  Fluid
f  Saturated liquid water
fg  Saturation change in property for pure water

G  Gravity term
G  Vapour-phase
GV  Gas in vapour-phase
GL  Gas in liquid-phase
GT  Total gas in system
GS  Superficial gas
g  Gravity term
g  Saturated steam
gt Gastube

h Homogeneous
h Hub
h Hydraulic

i 1, 2, 3, ..... 
i Inside
i Initial value
i Component in a mixture or solution

L Liquid-phase
LS Liquid superficial
LT Total liquid-phase
La Annular liquid film

ns Non-slip (homogeneous)
o Outside
o Initial value
p Pressure

r Radial component
r Reference point or fluid
r Reservoir property
r Formation rocks
r Relative property

S Salt
SL Salt in liquid-phase
ST Total salt in system
S  Slug/plug flow
sb Solid body rotation

T  Total
TP Two-phase
t Tube

V  Vapour-phase
VT Total vapour-phase
v  Viscous term

W  Water (substance)
WV Gaseous water (steam)
WL Liquid water
WT Total water (substance)
wh Wellhead
wb Wellbottom
z  Axial direction
Abbreviations

DHS  Downhole separator
Fr   Froude number
Ku   Kutateladze number
Re   Reynolds number
VFCS Vertical flow centrifugal separator
We   Weber number

ln   Natural logarithm
log  Logarithm to base 10

HLC  Homogeneous-liquid-continuous
HVC  Homogeneous-vapour-continuous

eff  Effective

NCG  Noncondensable gas(es)