Geothermal Capacity Building Program Indonesia - Netherlands

Geothermal Reservoir and Production Engineering Knowledge And Skills

FLOW MEASUREMENTS & PRODUCTION TESTING

This course was developed within WP 1.04 of the GEOCAP program

Figures captured from CalEnergy's video

TOPICS

- **Introduction**
- **Steam wells**
  - Vertical discharge using Lip pressure method
  - Measurement of steam using orifice plates
- **Two-phase wells**
  - Horizontal discharge using Lip pressure method
  - Separator method
- **Exercise**

FLOW MEASUREMENTS & PRODUCTION TESTING

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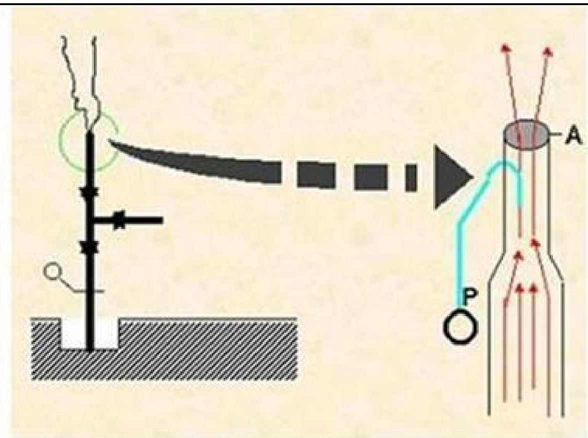
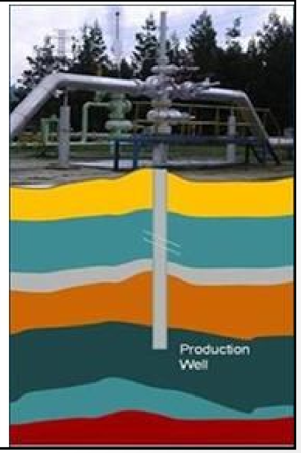
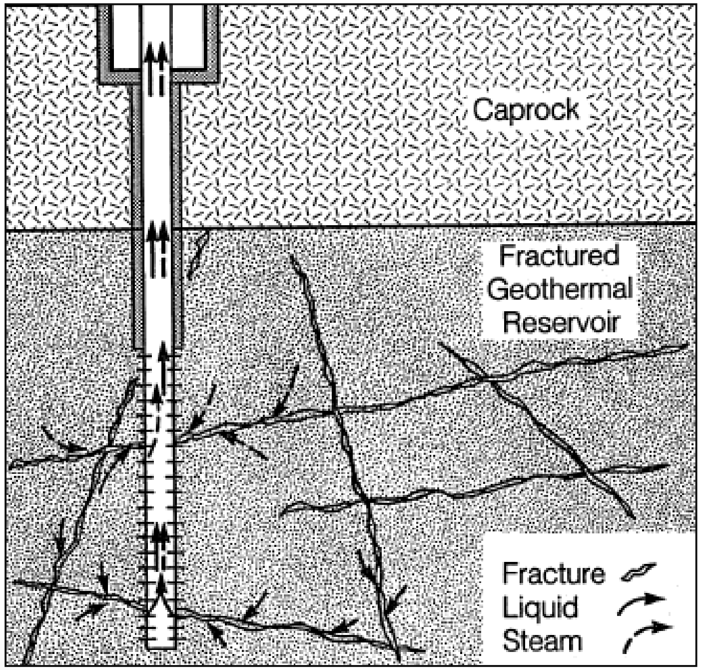




INTRODUCTION

Geothermal Wells

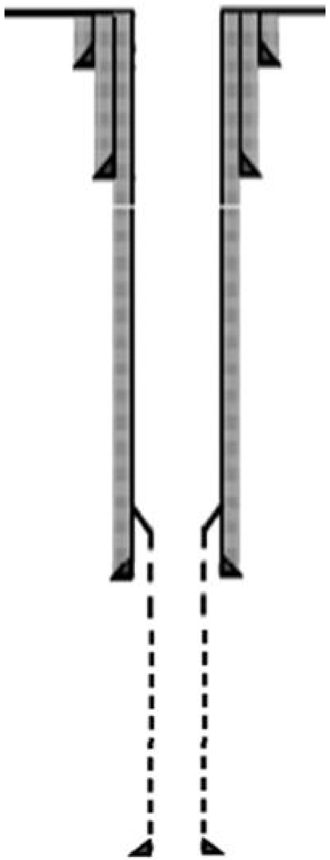
Well Drilling → Well Completion → Well Testing



- Geothermal Wells:
  - o Standard Well
  - o Big Hole Well
- Wells have multiple feed-zones

Well Drilling → **Well Completion** → **Well Testing**

- **Downhole Logging**
- **Waterloss Test &**
- **Gross Permeability Test**
- **Fall off Test**
- **PT Survey**
- **PTS Injection**

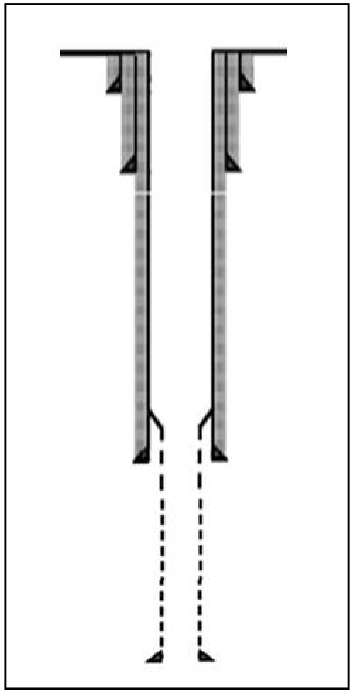


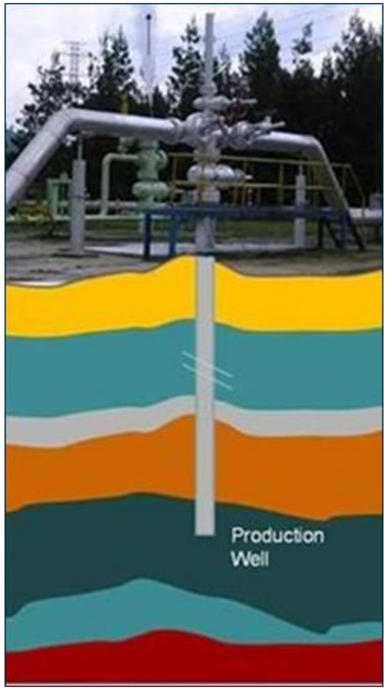
To determine:

- Casing condition
- Maximum depth of the well
- Obstruction or clogging
- Pressure and Temperature
- The depth of feed zone
- Productivty index (PI) & injectivity index (II) from feed zone
- Flow contribution from each feed zone

Geothermal Wells

Well Drilling → Well Completion → Well Testing





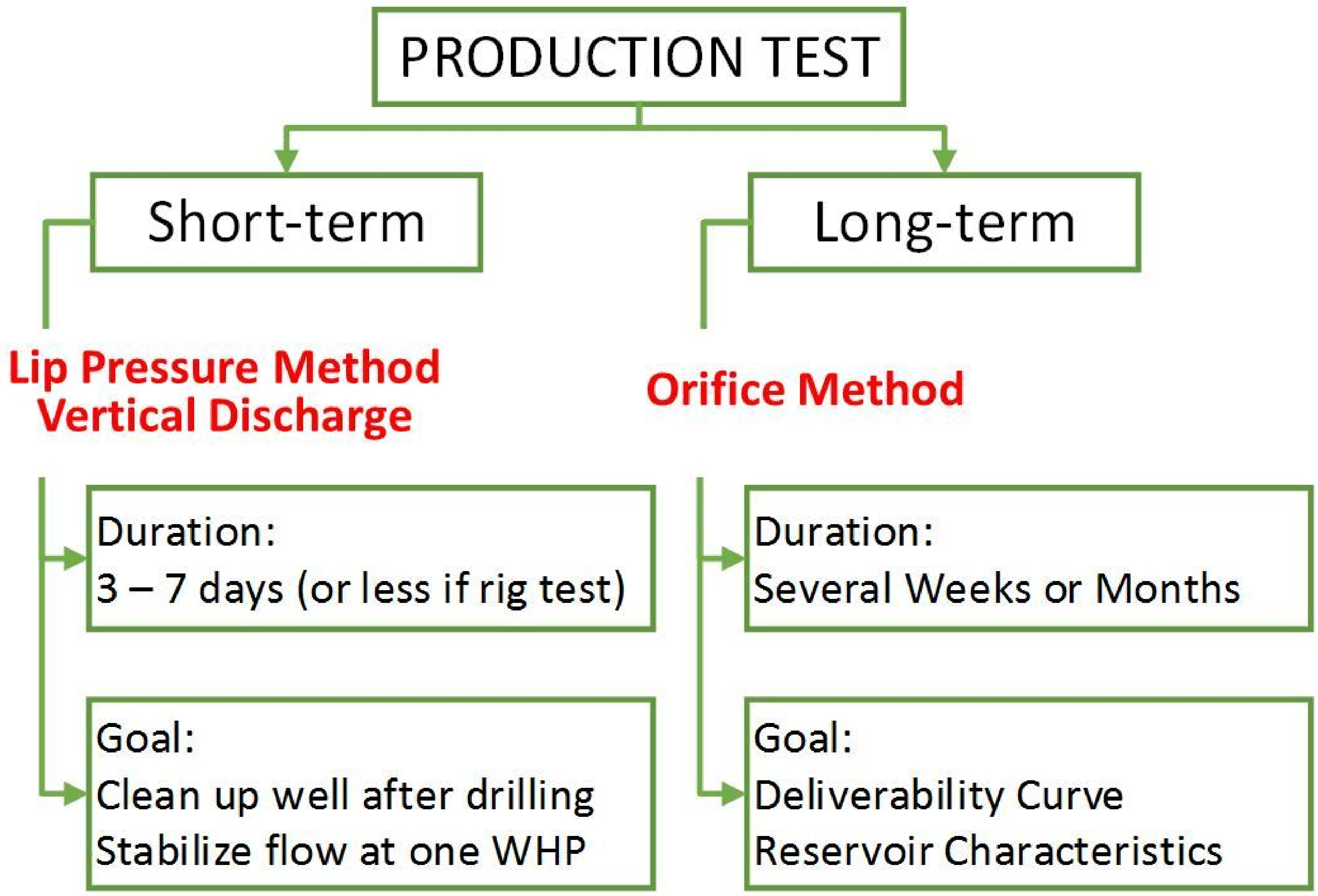
- Heating Up Test
- **Production Test**
- PTS Flowing Test
- Pressure Transient Test
- Tracer Test

Geothermal Production Test

PRODUCTION TEST

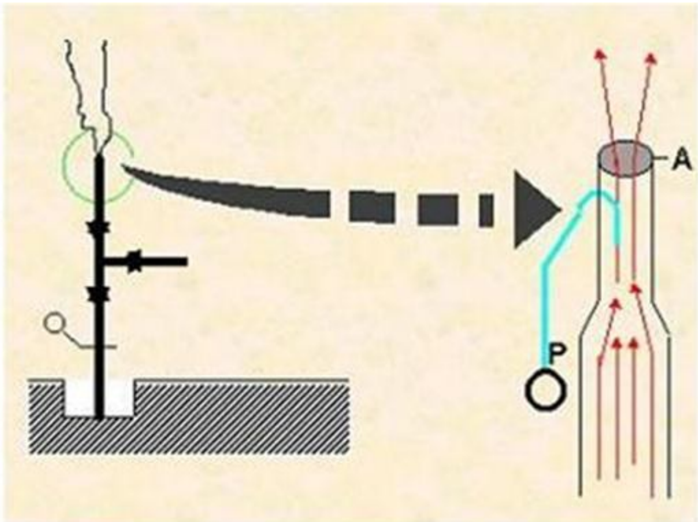
- **Short-term**
  - Duration:
    3 – 7 days (or less if rig test)
  - Goal:
    Clean up well after drilling
    Stabilize flow at one WHP
- **Long-term**
  - Duration:
    Several Weeks or Months
  - Goal:
    Deliverability Curve
    Reservoir Characteristics

STEAM WELLS


PRODUCTION TEST
Short-term
Long-term
Lip Pressure Method
Vertical Discharge
Orifice Method
Duration:
3 – 7 days (or less if rig test)
Goal:
Clean up well after drilling
Stabilize flow at one WHP
Duration:
Several Weeks or Months
Goal:
Deliverability Curve
Reservoir Characteristics

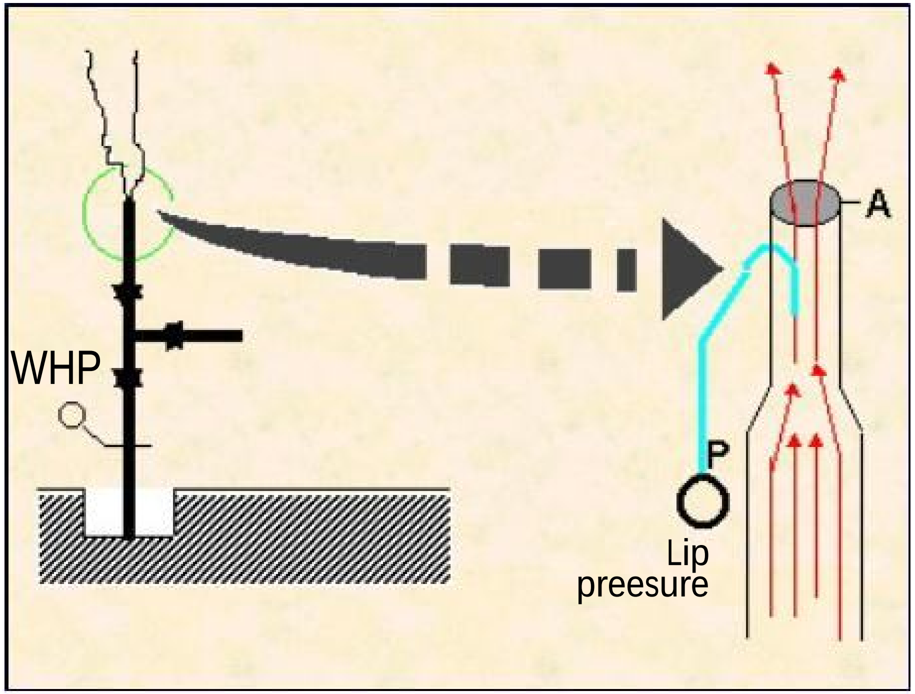
Lip Pressure Method - Vertical Discharge

- This method is based on empirical formula by Russel James (1966).
- The well was fully opened and the fluid discharged to atmosphere over several hours depending on local regulations.
- Vertical discharge is useful for giving an initial estimate of well potential and to determine what test equipment will be necessary to carry out a longer-term test



Gambar oleh Dudi Duardi, 1997

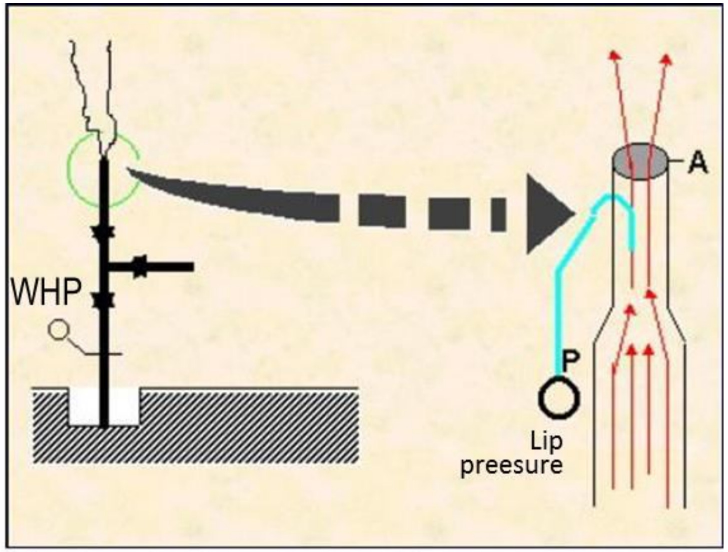
Russel James Formula



Gambar dari Dudi Duardi, 1997

$$\frac{G \times H^{1.102}}{p_c^{\,0.96}} = 0.184 \qquad \text{where} \qquad G = \frac{M}{3600 \times A}$$

Russel James Formula



Gambar dari Dudi Duardi, 1997

$$\frac{M \times H^{1.102}}{3600 \times A \times p^{0.96}} = 0.184$$

$$M = \frac{0.184 \times 3600 \times A \times p^{0.96}}{H^{1.102}}$$

Where:

P_c "lip pressure" [bar absolute]

H flowing enthalpy [kJ/kg]

G Mass flow rate through one unit area [tonnes/cm^2.sec]

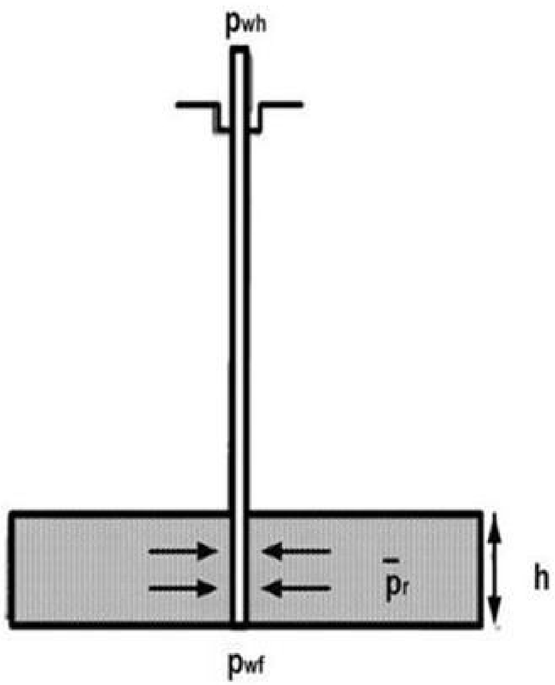
A Lip pressure pipe cross sectional area [cm^2]

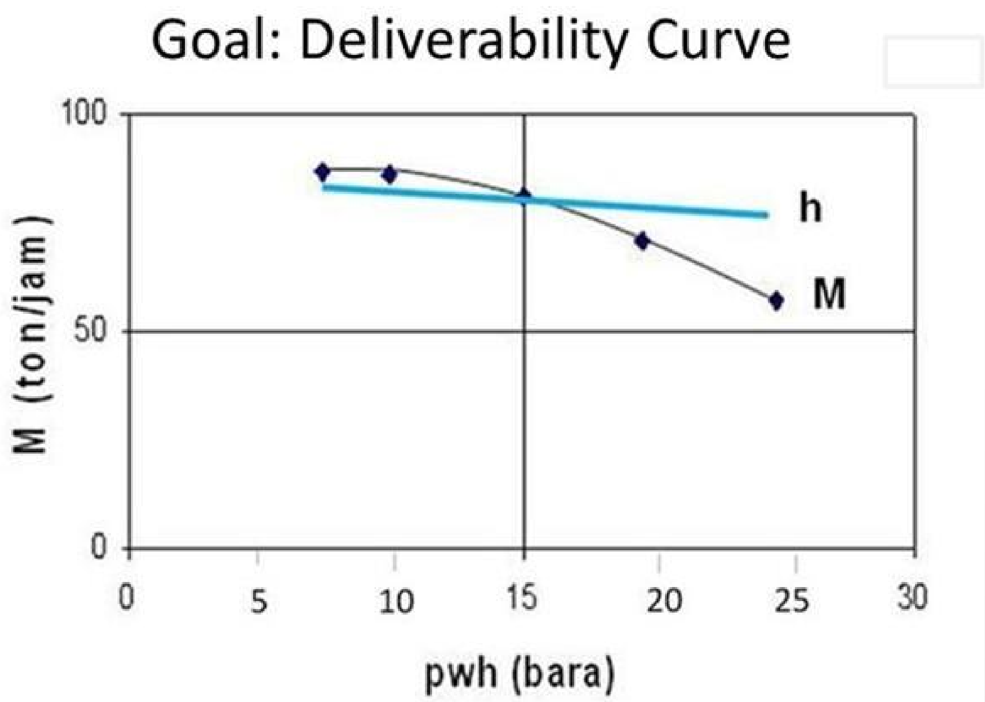
M Mass flow rate [tonnes/hour]

Long-term Production Test

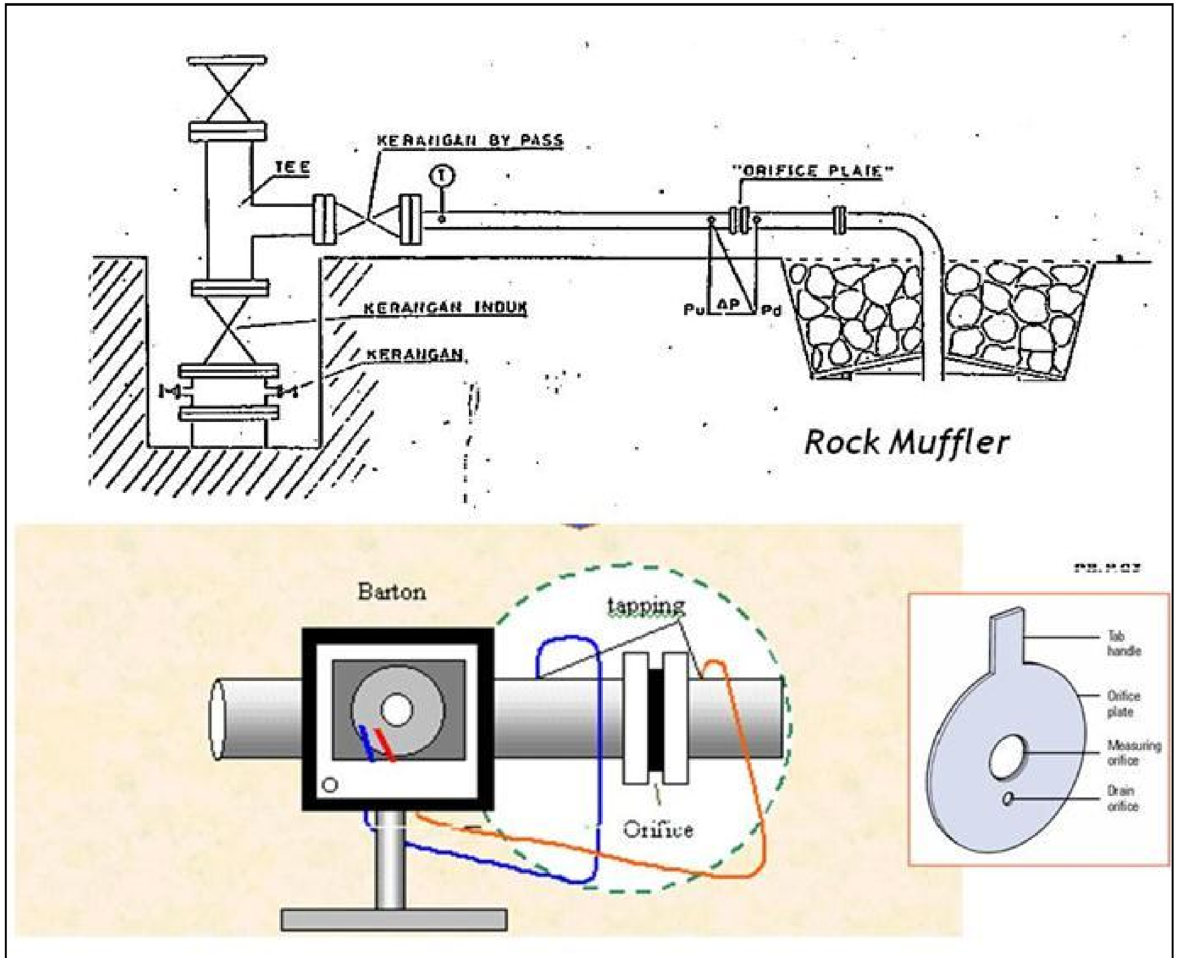
Objective:

- To get data of production rate and fluid enthalpy at various wellhead pressure.
- To know the type and properties of production fluid.





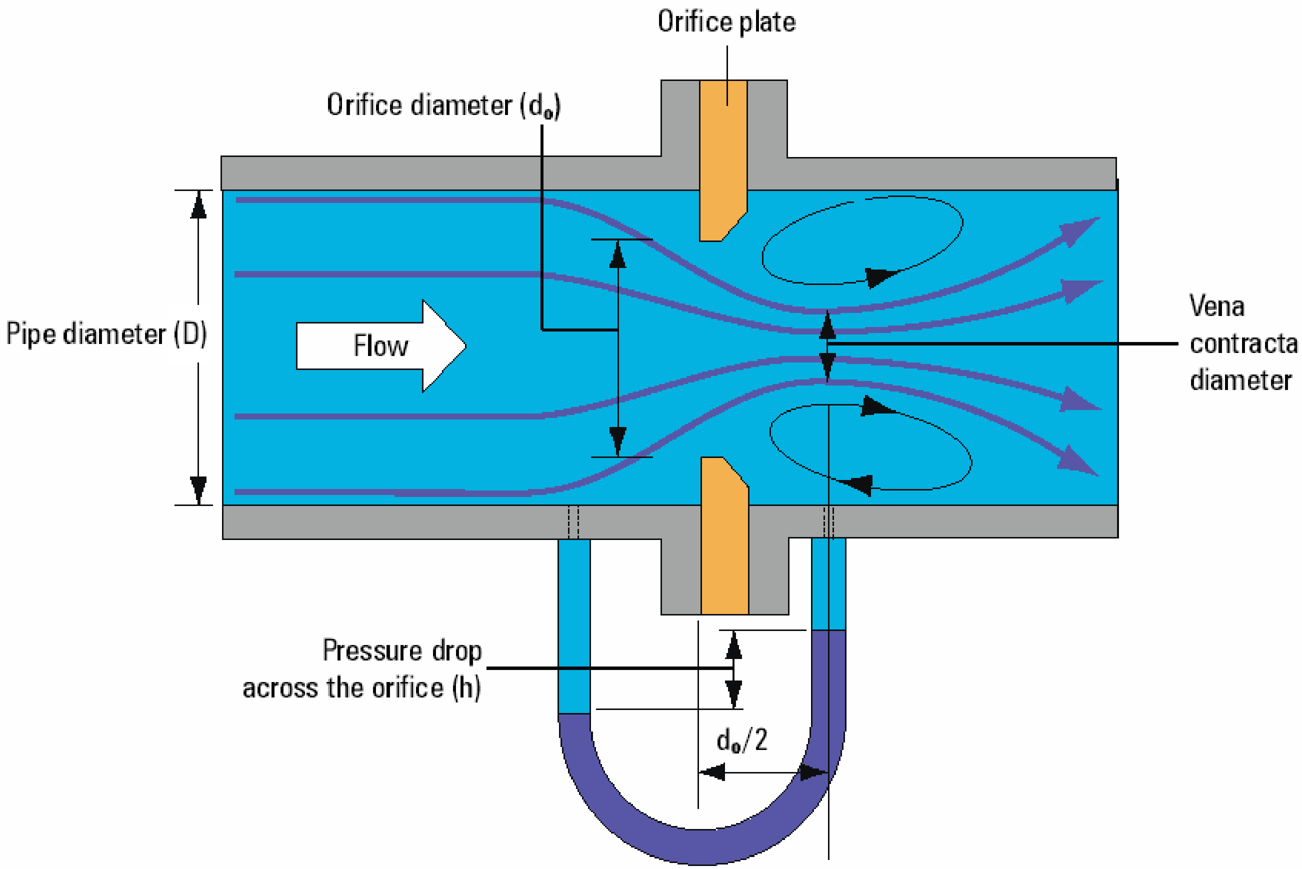
Orifice flow meter is installed between the flange on the connection of two pipes



Gambar oleh Dudi Duardi, 1997

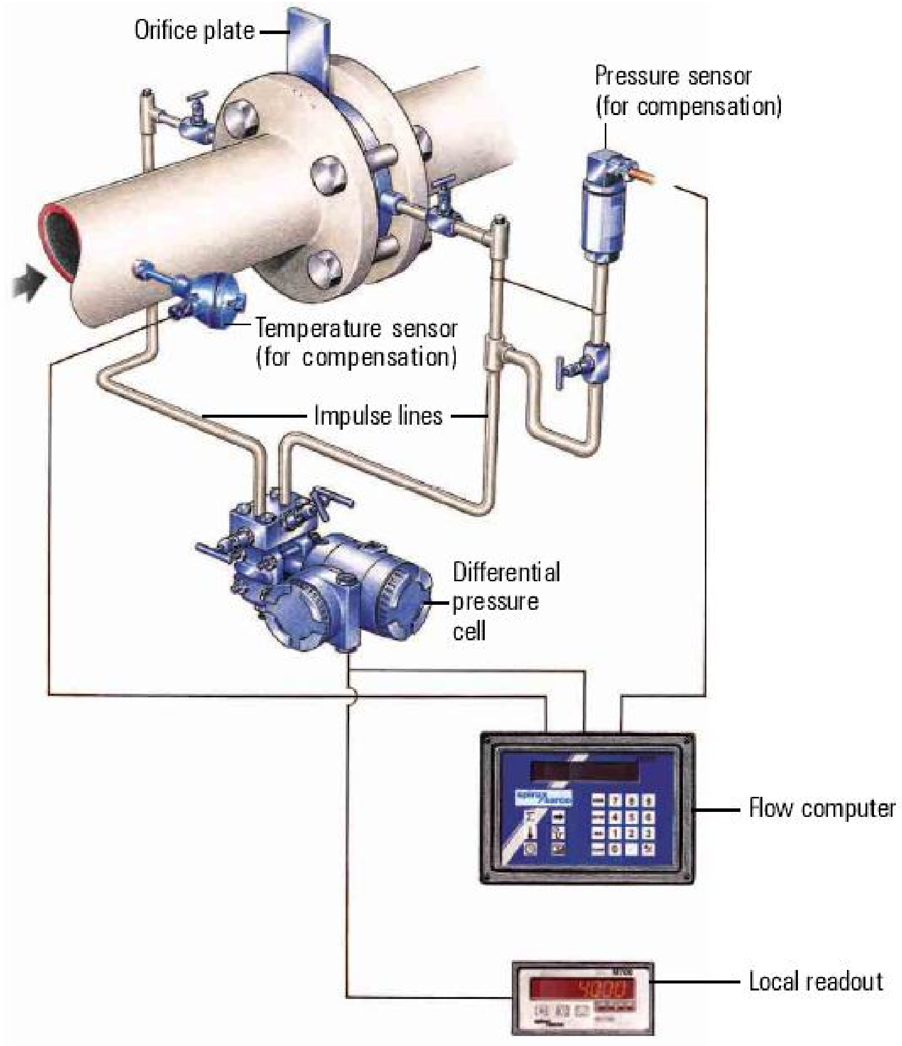
The well is opened and the fluid is discharged horizontally to a rock muffler

- The principle of measurement using orifice meter is measuring flow frictional losses (head loss) or pressure difference (P1 – P2) which pass through orifice plate.

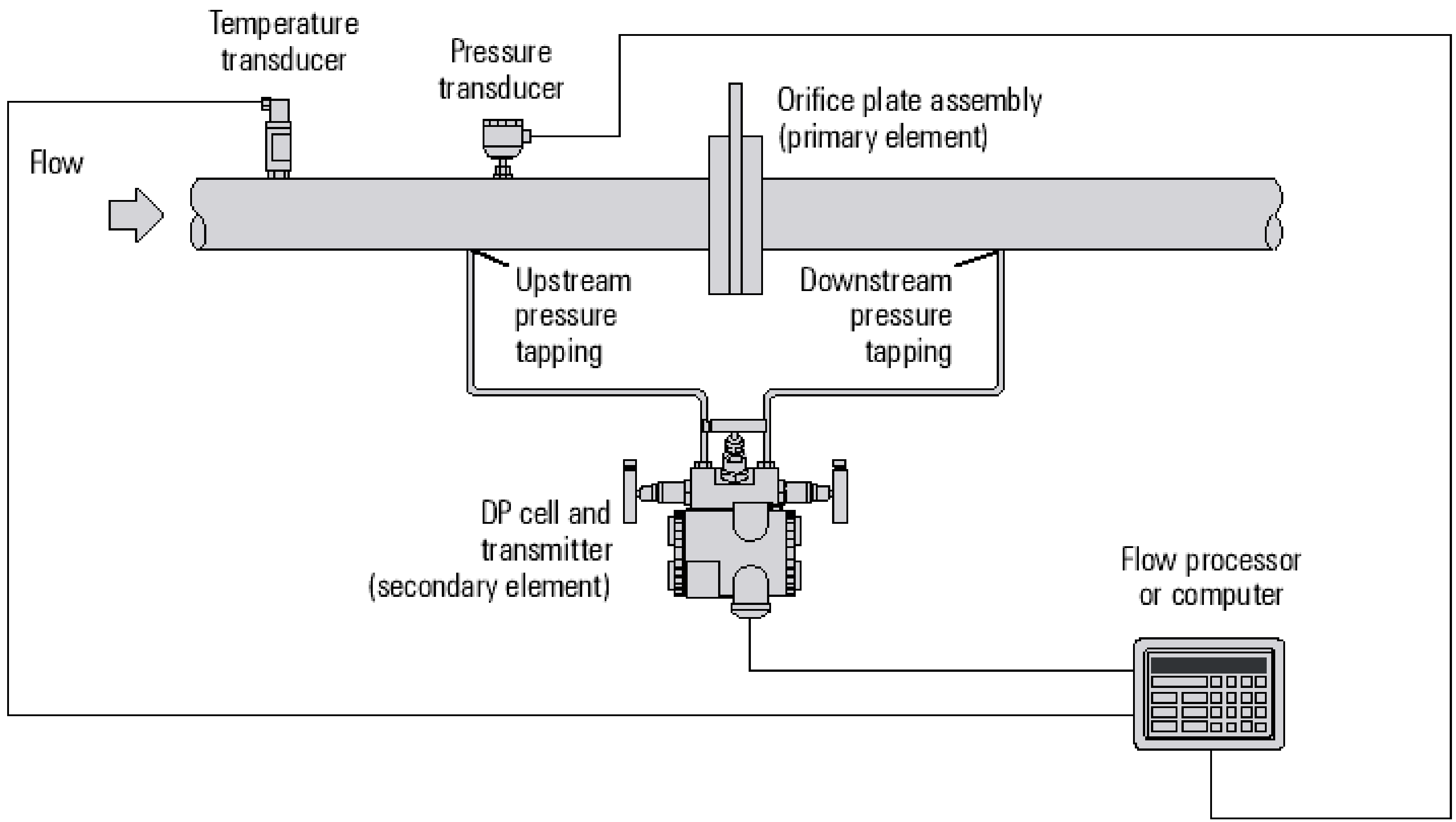


$$P_1 + \frac{\rho.u_1^{\;2}}{2.} + \rho.g.h_1 = P_2 + \frac{\rho.u_2^{\;2}}{2.} + \rho.g.h_2$$

The proper installation of orifice plate has regulated by ISO 5167 standard (Source: Ali Ashat, 2000)

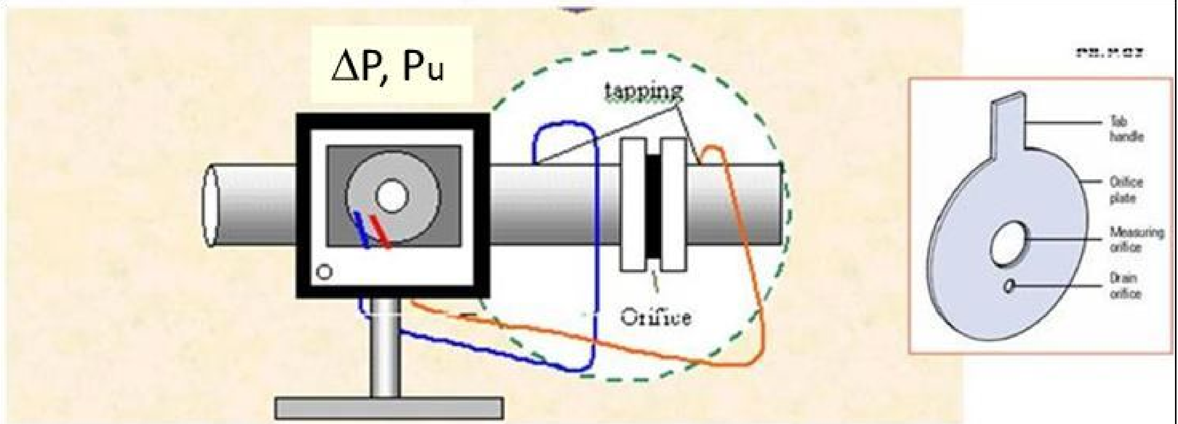


Schematic Installation of Orifice Meter
(Sumber: Ali Ashat, 2000)



Measurement using orifice plate

- Parameters to be measured: differential pressure (ΔP), upstream pressure (Pu) and temperature (Tu) at various well head pressure.



Gambar oleh Dudi Duardi, 1997

Mass flow rate is calculated using equation:

$$M = 0.03959172 \times c \times Z \times e \times E \times d^2 \sqrt{\frac{\Delta p}{\upsilon_g}}$$

Calculation of mass flow rate:

$$M = 0.03959172 \times c \times Z \times e \times E \times d^2 \sqrt{\frac{\Delta p}{\upsilon_g}}$$

M : Mass flow rate (ton/hour)

Δp : differential pressure (bar)

ν_g : spesific volume of steam (m^3/kg)

$$e = 1 - (0.41 - 0.35m^2) \times \frac{1}{k} \times \frac{\Delta p}{P_u}$$

k : adibatic index (1.33 for saturated steam dan 1.3 for superheated steam)

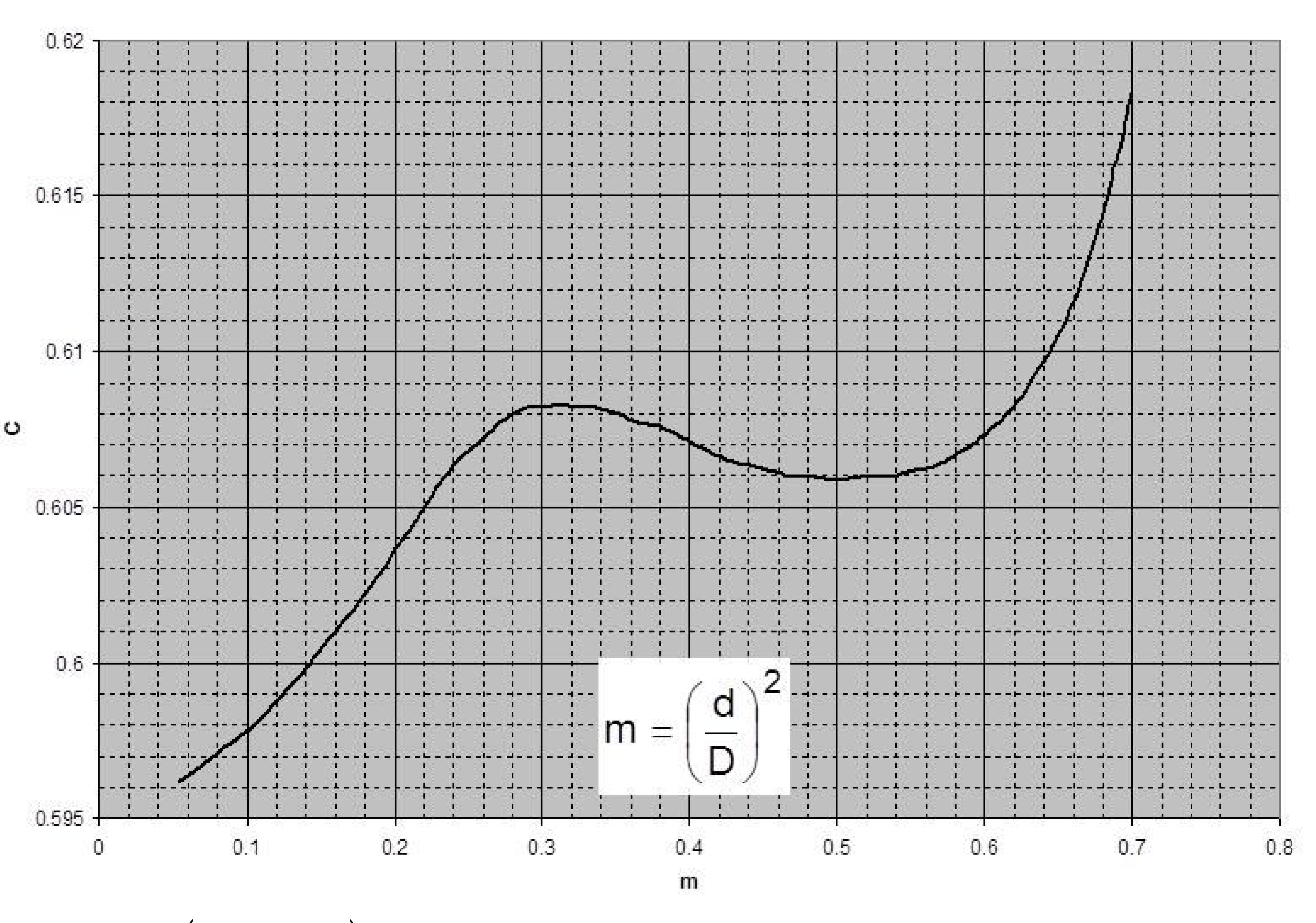
P_u : Upstream pressure

$$m = \left(\frac{d}{D}\right)^2 \Rightarrow$$

d: Inside diameter of orifice plate

D: Inside diameter of the pipe

C = f (m) and it is determined using the following correaltion



$$E = \left(1 - m^2\right)^{-0.5}$$

Formula:

$$M = 0.03959172 \times c \times Z \times e \times E \times d^2 \sqrt{\frac{\Delta p}{\upsilon_g}}$$

$$\Rightarrow \quad M = C\sqrt{\frac{\Delta p}{\upsilon_g}}$$

Where:

M : Mass flow rate (ton/hour)

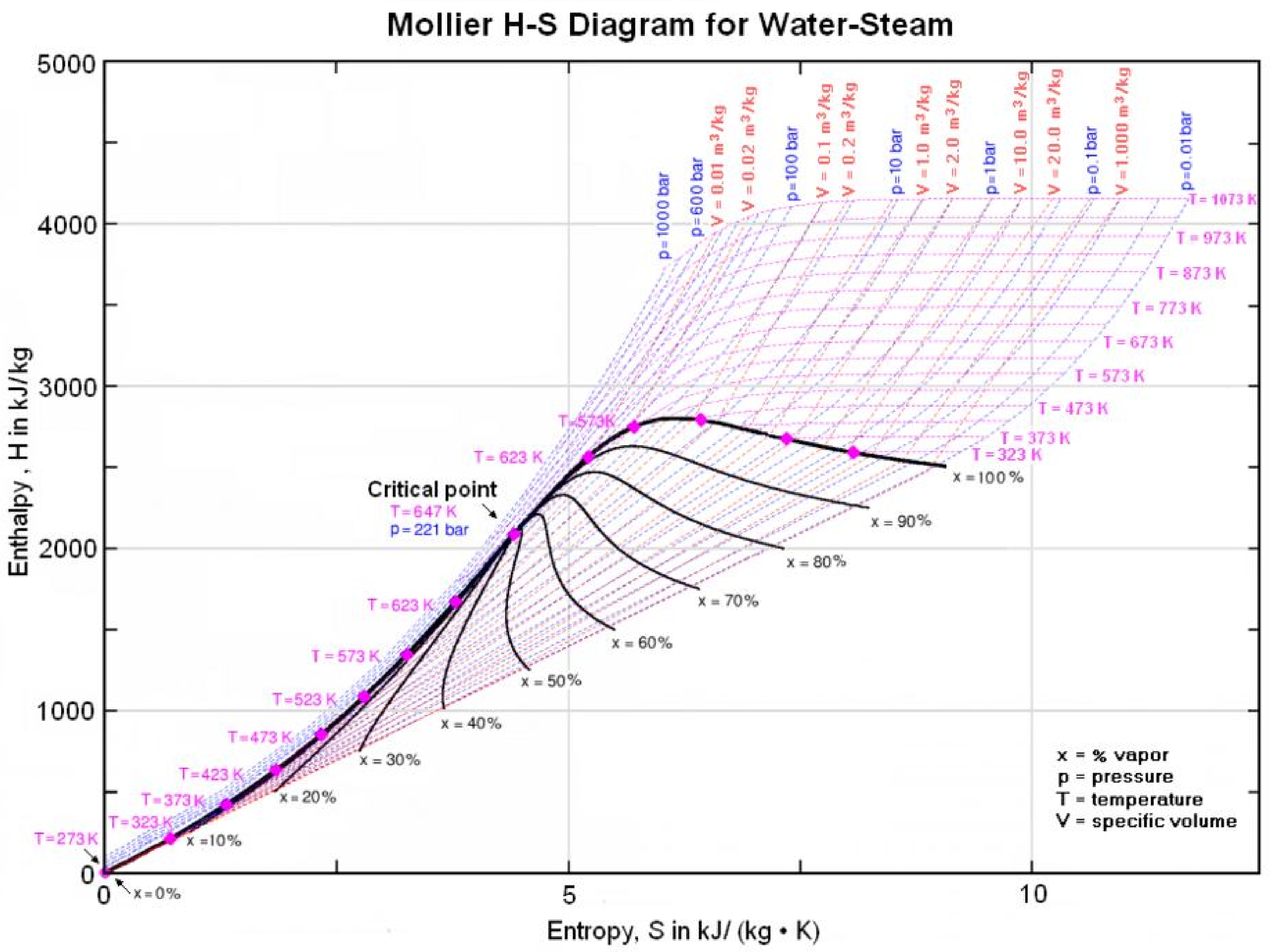
Δp : Differential pressure (bar)

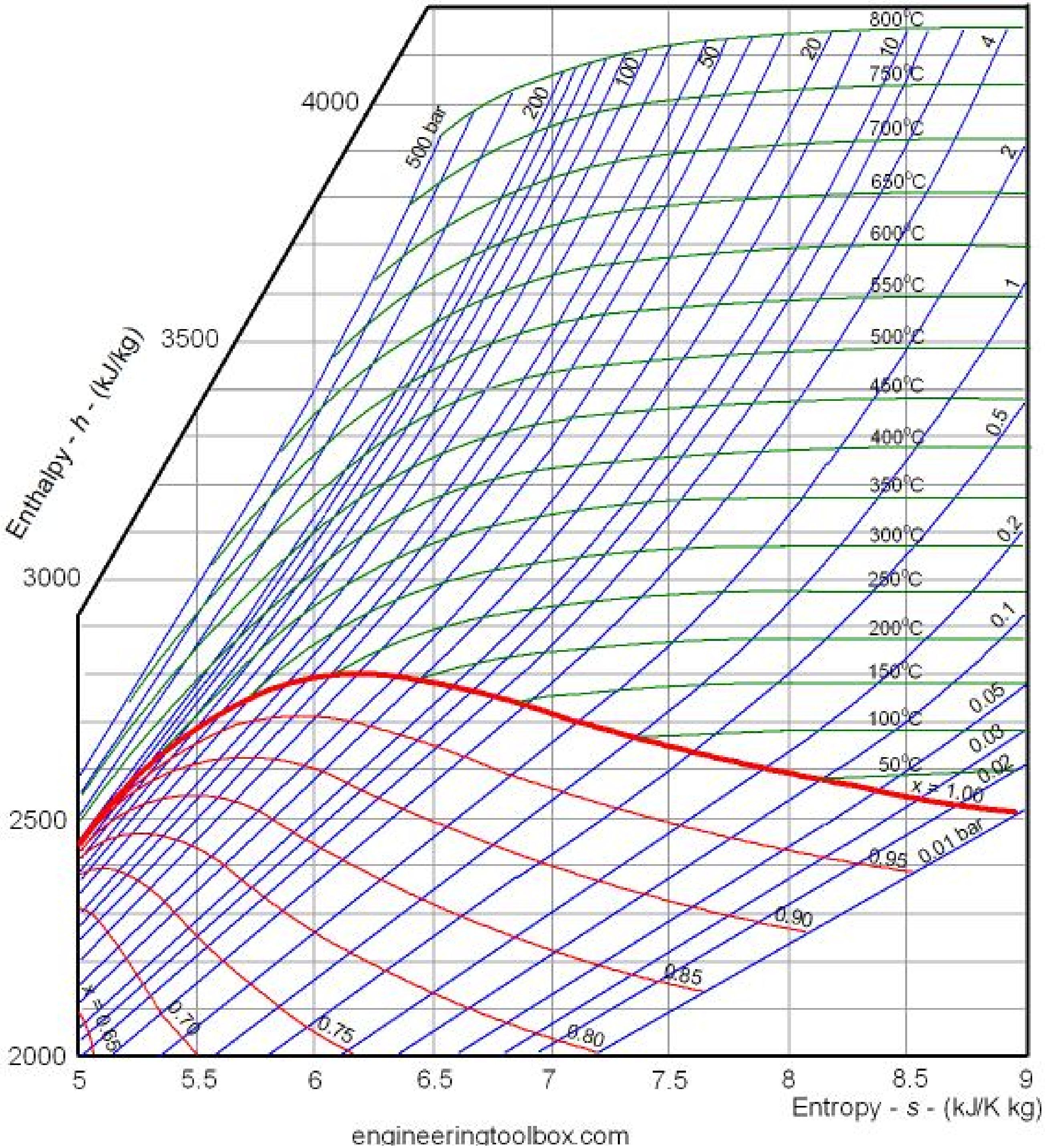
ν_g : Spesific volume of steam (m^3/kg)

C : Orifice coefieciént (dimentionless)

If orifice measured the water flow rate, therefore e = 1

Enthalpy and steam quality from Mollier Diagram





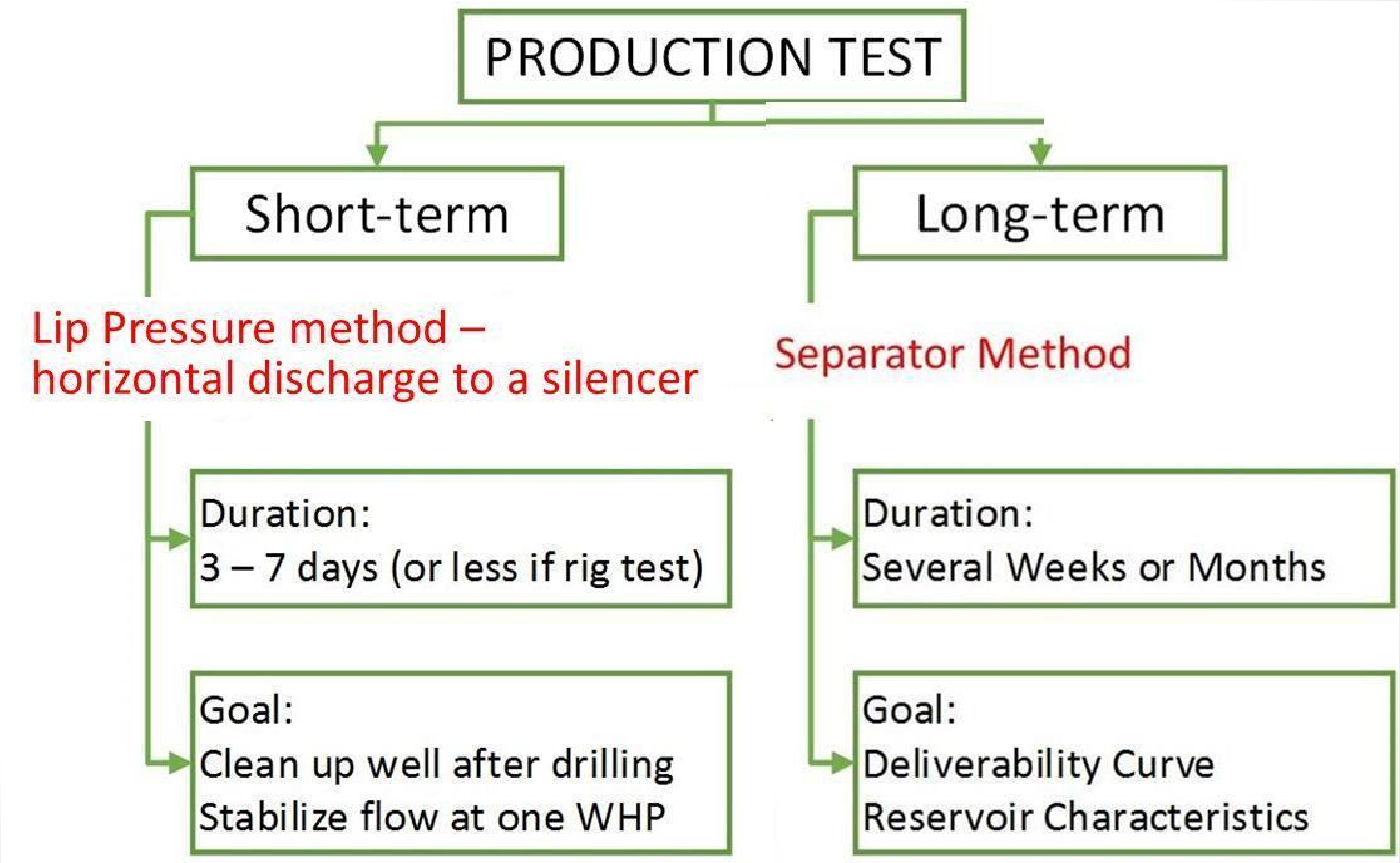
Enthalpy - h - (kJ/kg)
Entropy - s - (kJ/K kg)
2000
2500
3000
3500
4000
5
5.5
6
6.5
7
7.5
8
8.5
9
800°C
750°C
700°C
650°C
600°C
550°C
500°C
450°C
400°C
350°C
300°C
250°C
200°C
150°C
100°C
50°C
500 bar
200
100
50
20
10
4
2
1
0.5
0.2
0.1
0.05
0.03
0.02
0.01 bar
x = 1.00
0.95
0.90
0.85
0.80
0.75
0.70
x = 0.65
engineeringtoolbox.com

Examples of Data

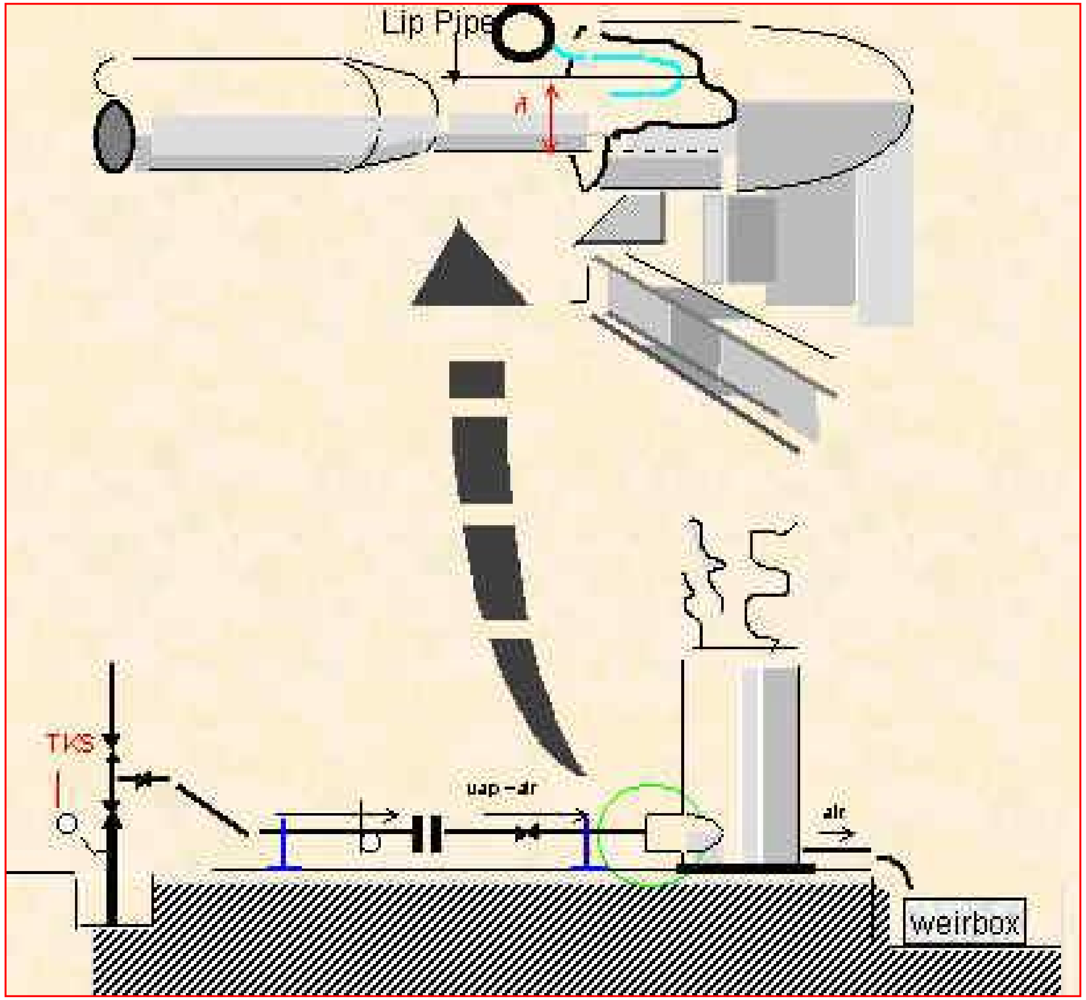
(Source: Ali Ashat)

TANGGAL	JAM	TKS (KSC)	PU (KSC)	DP (KSC)	TU (oC)	KETERANGAN
24-11-97	08.00	33.00	Dibleeding			Persiapan uji datar/tegak.
25-11-97	09.45	6.20	P.Lips =	2,90	Ksc	Dibuka tegak pipa tegak 8"
	10.00	5.80	P.Lips =	2,55	Ksc	(195 mm).
	10.45	5.80	P.Lips =	2,55	Ksc	
25-11-97	10.45	10.10	8.90	1.213	178.00	Jam 10.45 WIB mulai di uji datar
	14.00	10.10	8.90	1.213	178.00	dengan pipa datar 8" (198,4 mm)
	17.30	9.50	7.81	1.132	173.00	dan orifice 164,73 mm.
26-11-97	00.00	9.30	7.60	1.050	172.00	
	06.00	8.20	6.94	1.020	168.50	
	12.00	7.50	5.91	1.423	163.00	Jam 12.00 TKS diset ke 7.5 ksc.
	18.00	7.50	6.33	1.035	164.50	
27-11-97	00.00	7.50	6.56	1.035	166.00	
	06.00	7.50	6.33	1.019	164.50	
	12.00	7.50	6.33	0.995	164.50	
	18.00	7.50	6.33	0.979	164.50	
28-11-97	00.00	7.50	6.33	0.970	164.50	
	06.00	7.50	6.33	0.954	164.50	
	12.00	7.50	6.33	0.922	164.50	
	18.00	7.50	6.33	0.906	164.00	
29-11-97	00.00	7.50	6.33	0.898	164.00	

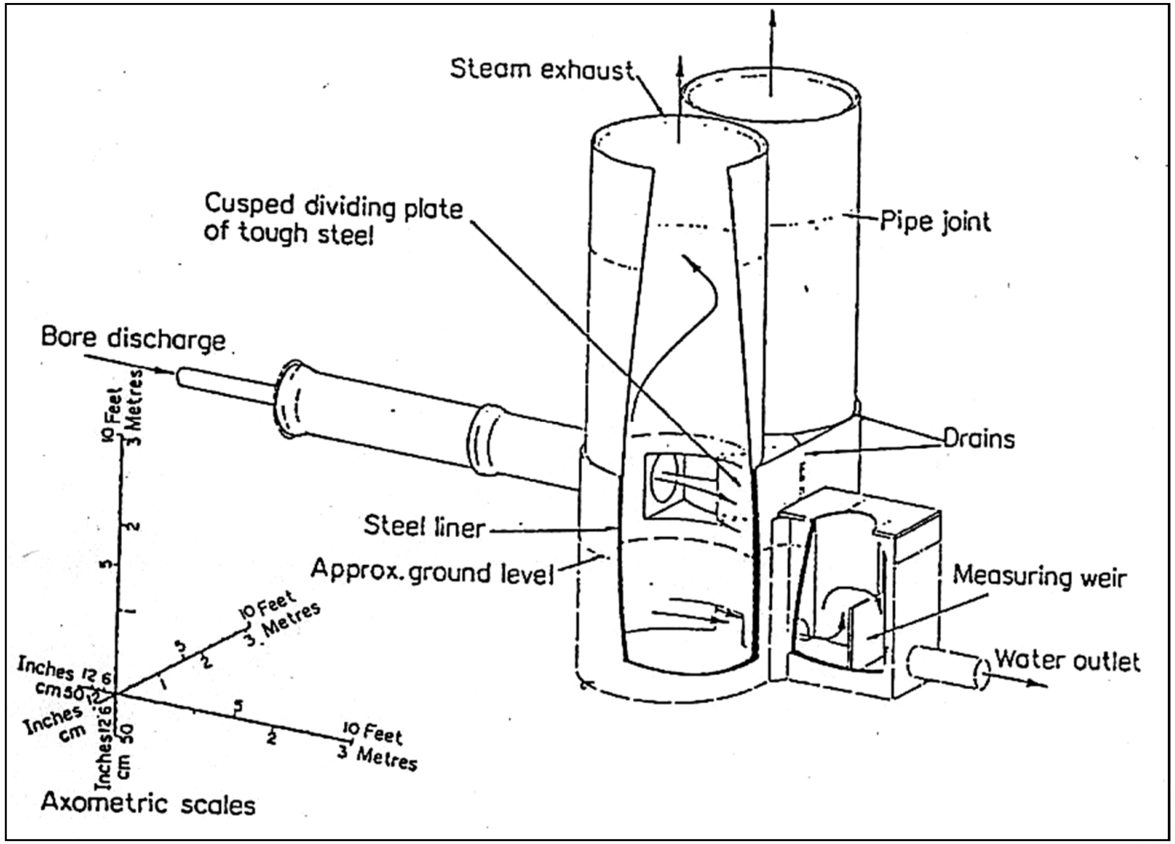
Two-phase Wells



Lip Pressure Method –
Horizontal Discharge to a Silencer

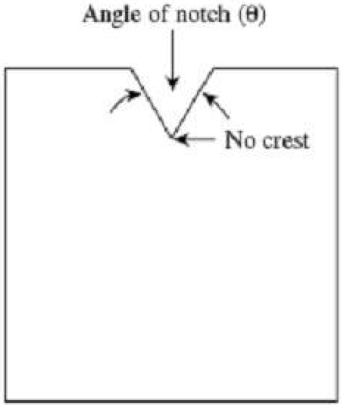


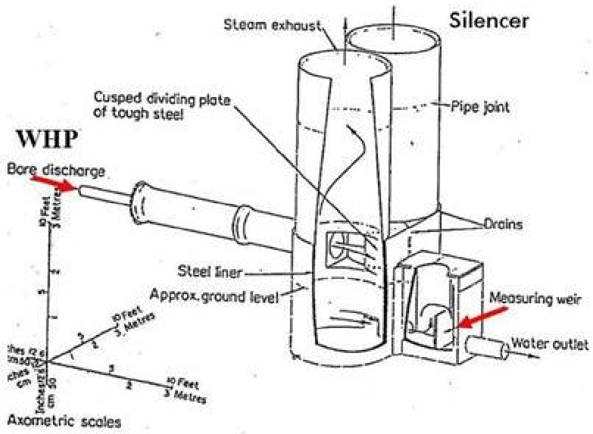
- The well is opened at a particular wellhead pressure and the fluid is flowed into the silencer (atmospheric separator).
- The height of water pass the weir box is measured, as well as temperature.



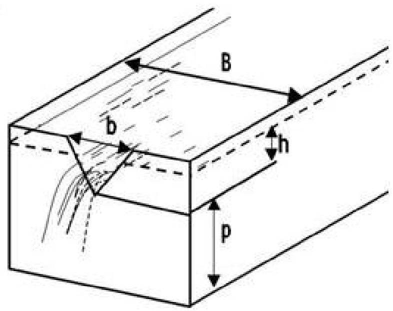
Measurement of water from silencer using weir box

Triangular Weirbox



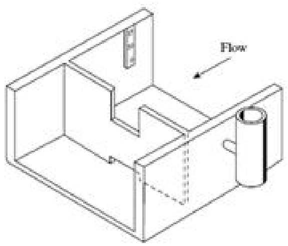


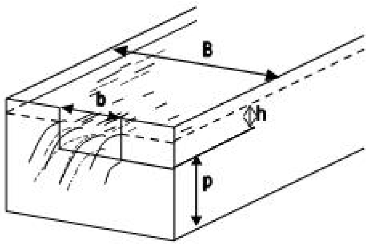
90⁰ V Notches



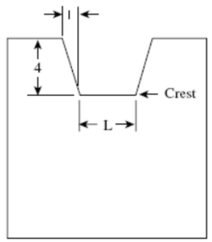
h, p, b, B dalam meter
Watm dalam t/h

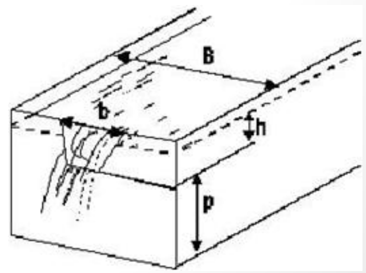
Rectangular **Weirbox**



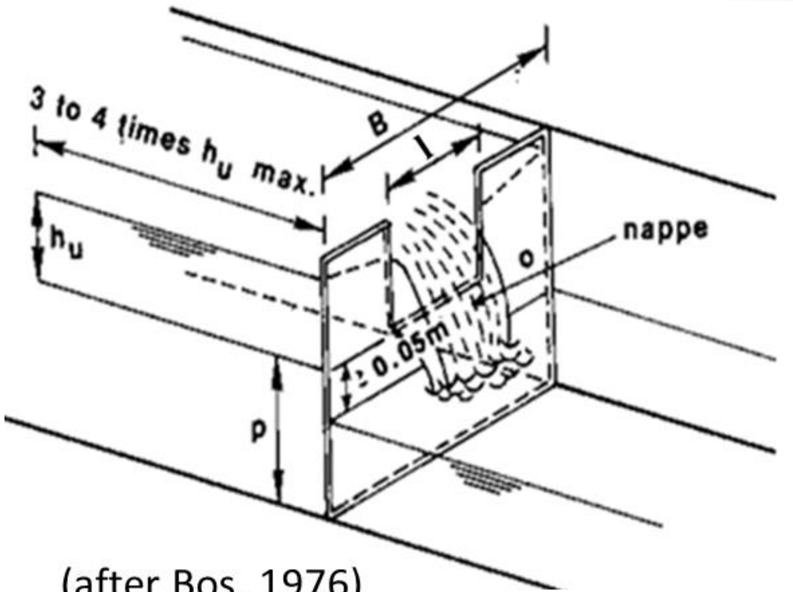


Suppressed Weirbox





Rectangular Weir Box

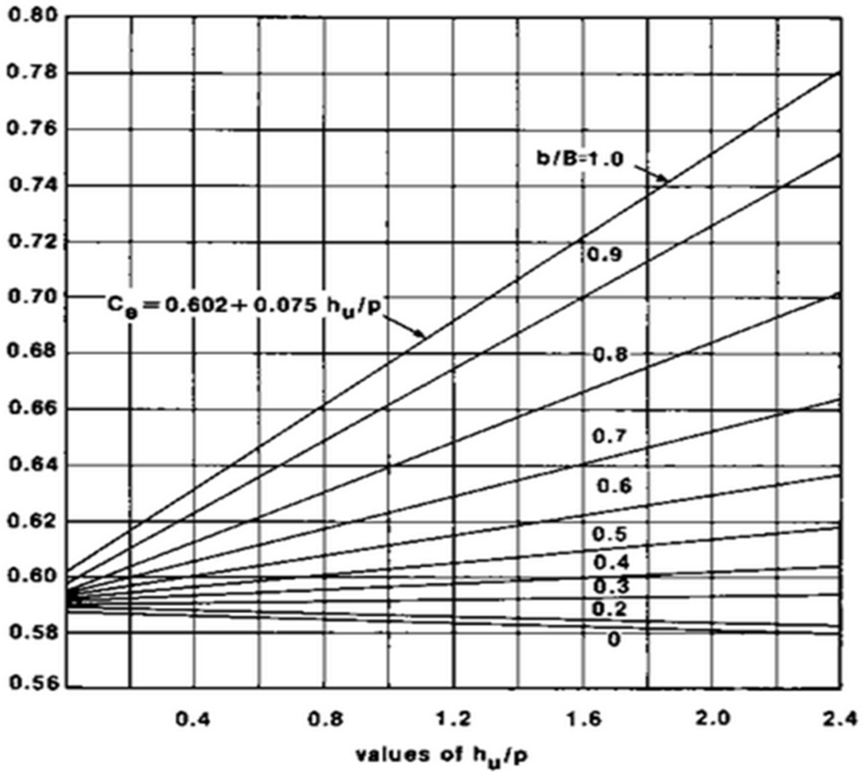


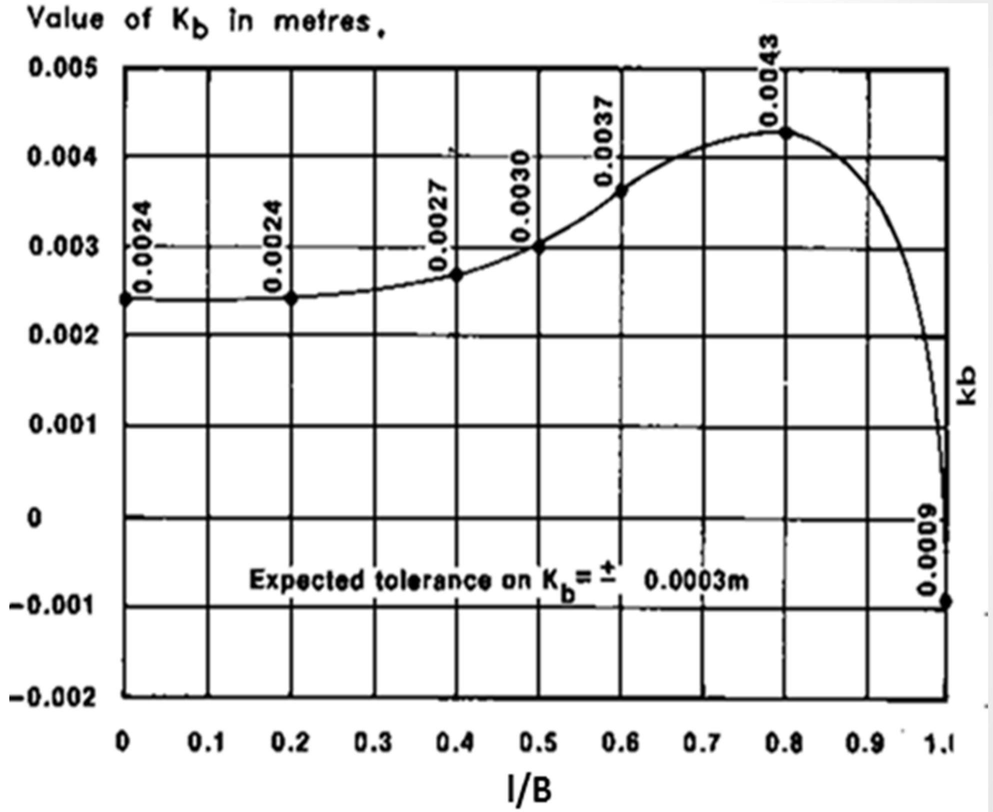
(after Bos, 1976)

$$W_{atm} = \frac{2}{3}\sqrt{2g} * C_e * (k_b + l) * (h_u + 0.0001)^{1.5} * \rho$$

Watm	: Water Mass Rate (kg/s)
C_e	: Effective Free Flow discharge coefficient ($m^{0.5}$)
l	: Effective Width of Weir (m)
h_u	: Head Water Measurement (m)
k_b	: Width Correction (m)
g	: Gravity Force (m/s^2)
ρ	: Fluid Density (kg/m^3)
h_u	: Max head water (m)

The Ce coefficient and width correction for rectangular weir





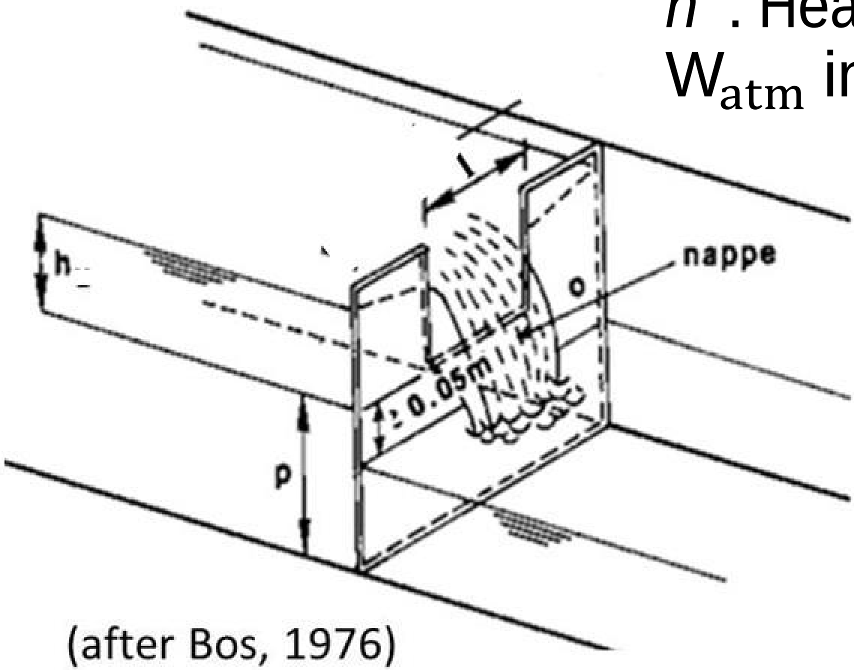
(Kindsvater and Carter, 1957)

Simplified Formula for Rectangular Weir Box

For field application, simplified equation of a rectangular weir is commonly used, by assuming C_e = 0.588 $m^{0.5}$ and water temperature 98°C, while k_b value is ignored.

$$W_{atm} = 6000 * l * h^{1.5}$$

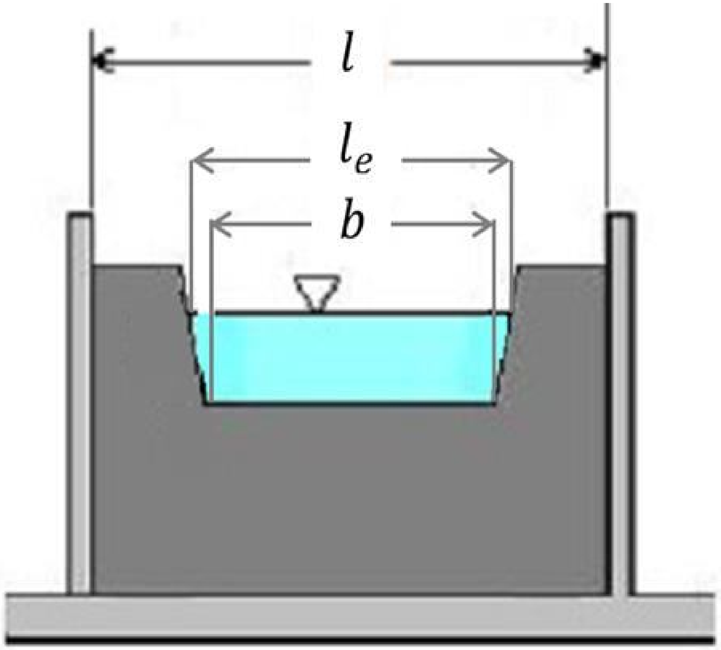
l : Effective Width of Weir (m)
h : Head Water Measurement (m)
W_{atm} in ton/hour



(after Bos, 1976)

Trapezoidal (Cipolletti) Weir Box

The trapezoidal or cipolletti weir is similar to a rectangular weir except the sides of the weir opening are trapezoidal in shape. The design is good for measuring medium water flow rates.



(Shen, 1960)

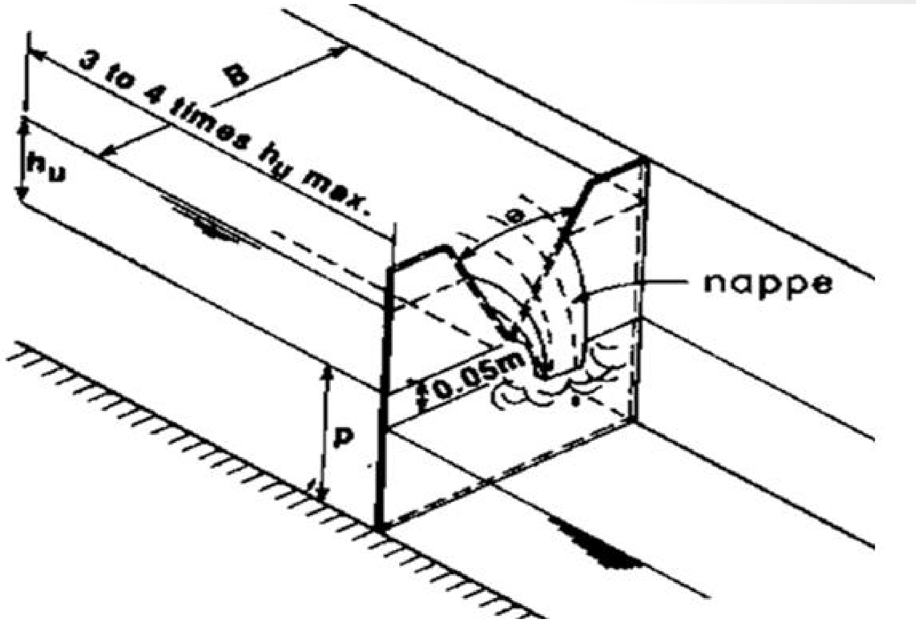
In field application, the simplified equation for trapezoidal weir nearly the same as for the rectangular weir.

$$W_{atm} = 6290 * l * h^{1.5}$$

It is obtained by assuming C_e = 0.616 $m^{0.5}$ and water temperature 98^{o}C, while k_b value is ignored.

Where W_{atm} in ton/hour, l and h in meter

V- notch Weir Box



(after Bos, 1976)

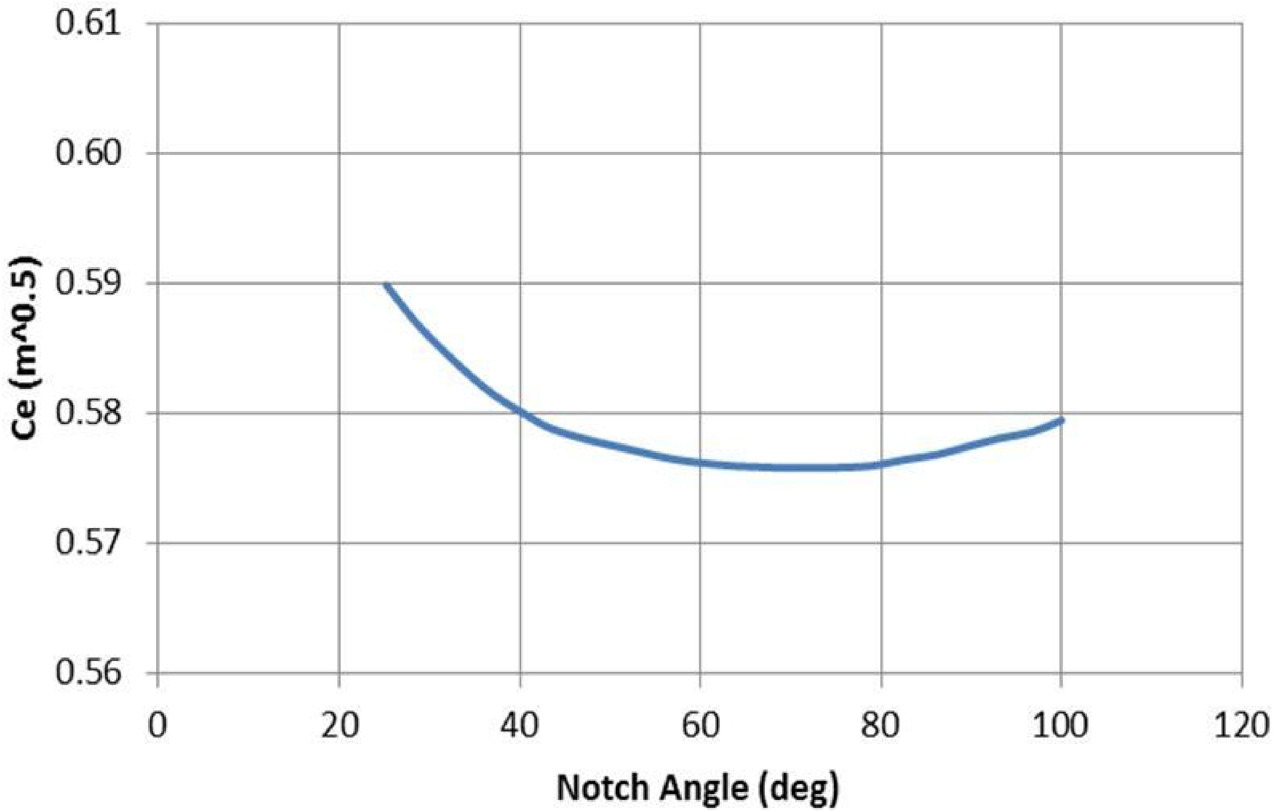
$$W_{atm} = \frac{8}{15}\sqrt{2g} * \frac{\theta}{2} * C_e * (h_u + k_h)^{2.5} * \rho$$

W_{atm} : Water mass rate (kg/s)
C_e : Effective free flow discharge coefficient ($m^{0.5}$)
h_u : Water head measurement (m)
k_h : Head correction (m)
θ : Central angle of V-notch (m)
g : Gravity force (m/s^2)

V- notch Weir Box

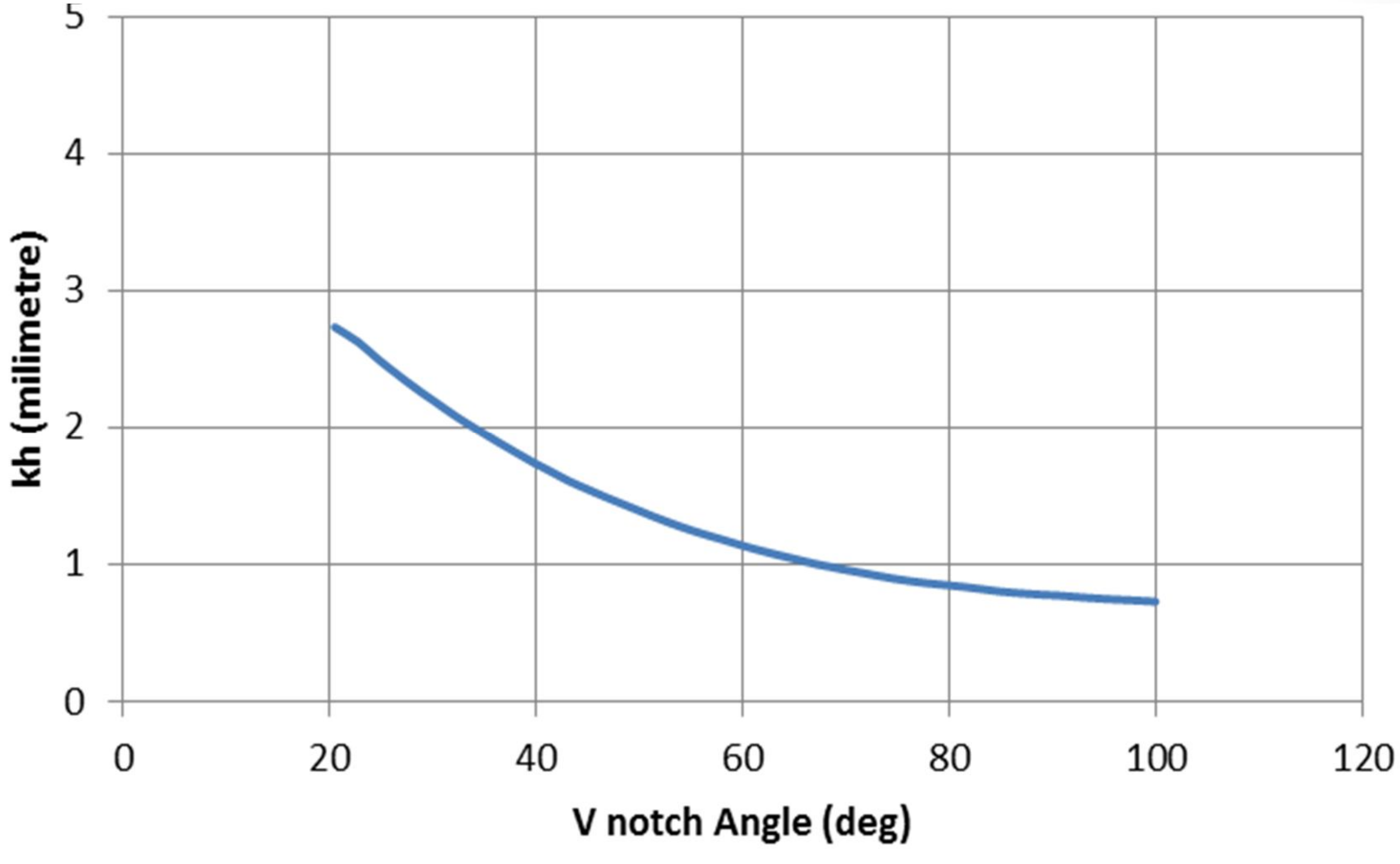
$$C_e = 1.543x10^{-9} * \theta^4 - 4.535x10^{-7} * \theta^3 + 5.294x10^{-5} * \theta^2 - 2.855x10^{-3} * \theta + 6.348x10^{-1}$$

$$k_h = 0.0004 * \theta^2 - 0.071 * \theta + 3.984$$



Shen (1960)

V- notch Weir Box



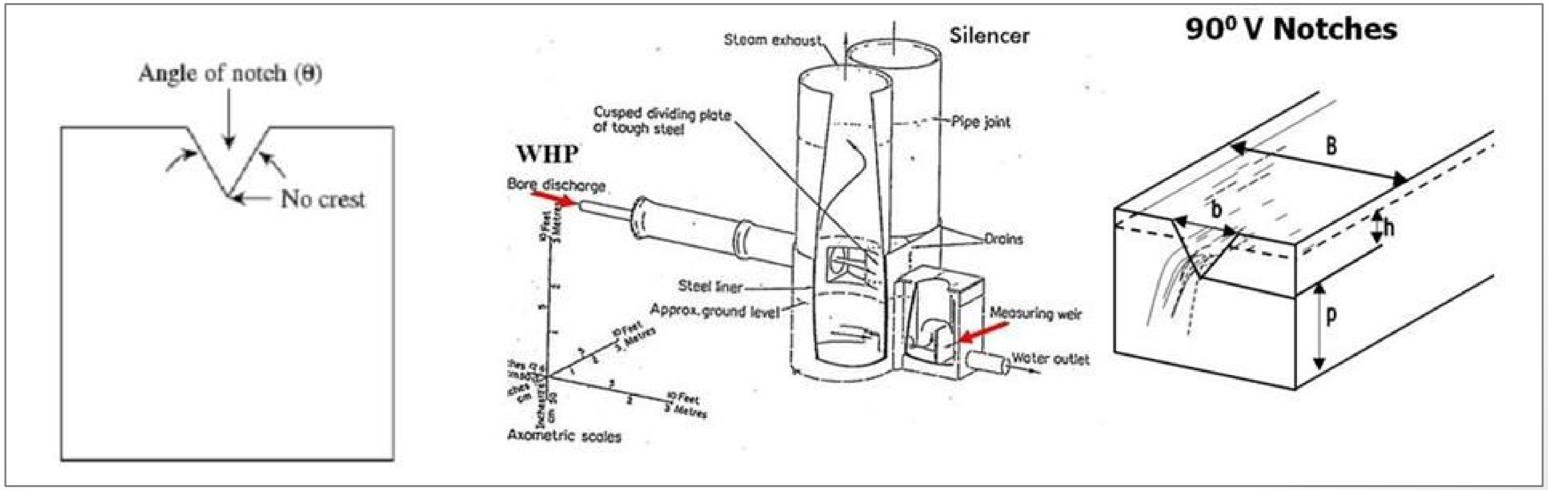
Shen (1960)

Simplified Formula for V- notch Weir Box

For field application, the simplified equation is commonly used by assuming C_e = 0.578 $m^{0.5}$ and water temperature 98°C, while k_h value is ignored. It should be noted that the simplified equation is only applied for notch angle (θ) = 90°.

$$W_{atm} = 4720 * h^{2.5}$$

Where W_{atm} in ton/hour and h in meter

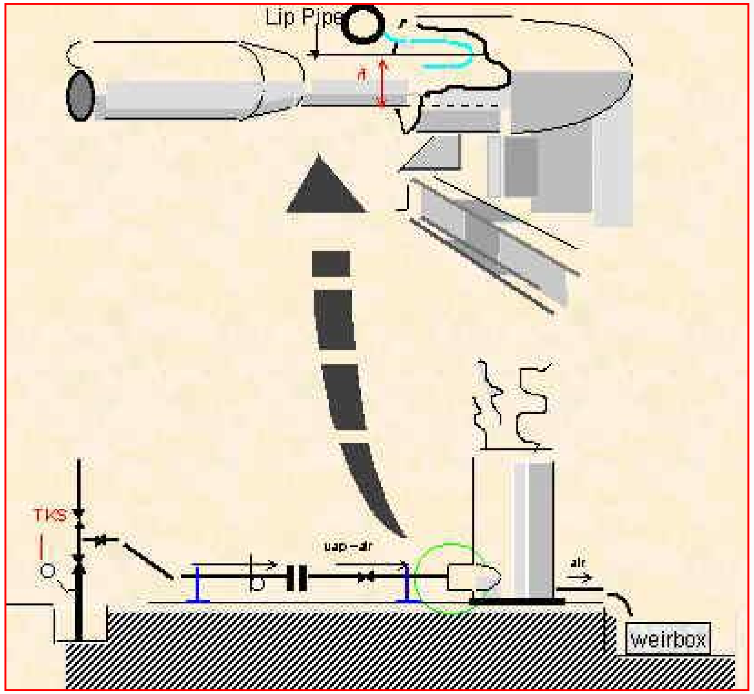


Russel James formula
for calculating mass flow rate and enthaply

$$Y = \frac{W_{atm}}{A \times p^{0.96}}$$

$$H = \frac{2675 + 925 \times Y}{1 + 7.85 \times Y}$$

$$M = \frac{W_{atm} \times 2258}{2675 - H}$$

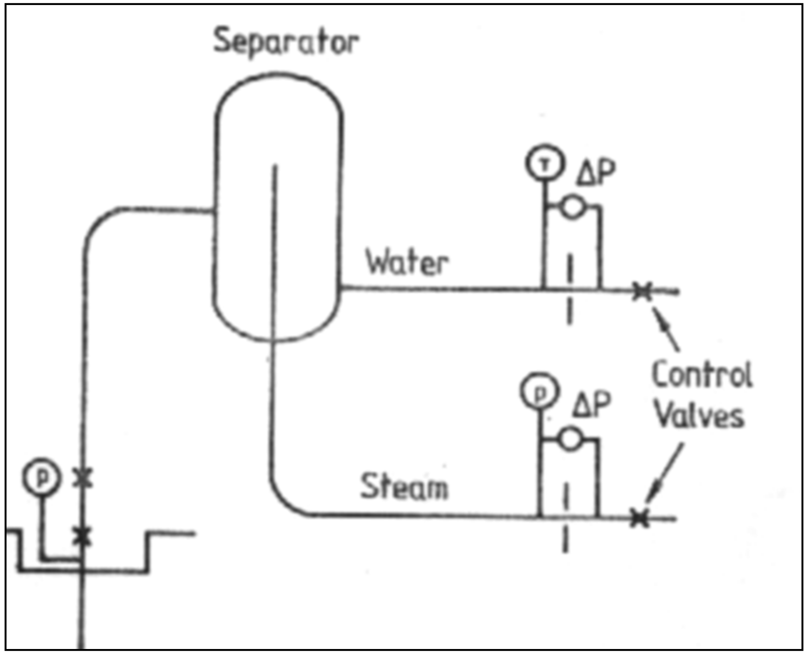


M : Mass flow rate from the welll (ton/Jam)
H : Fluid enthalphy (kJ/kg)
P : Lip pressure (bara)
W_{atm} : Water mass flow rate measured in the weir box at atmospheric condition

Nenny Saptadji/ITB

Separator Method
Measurement using orifice plates

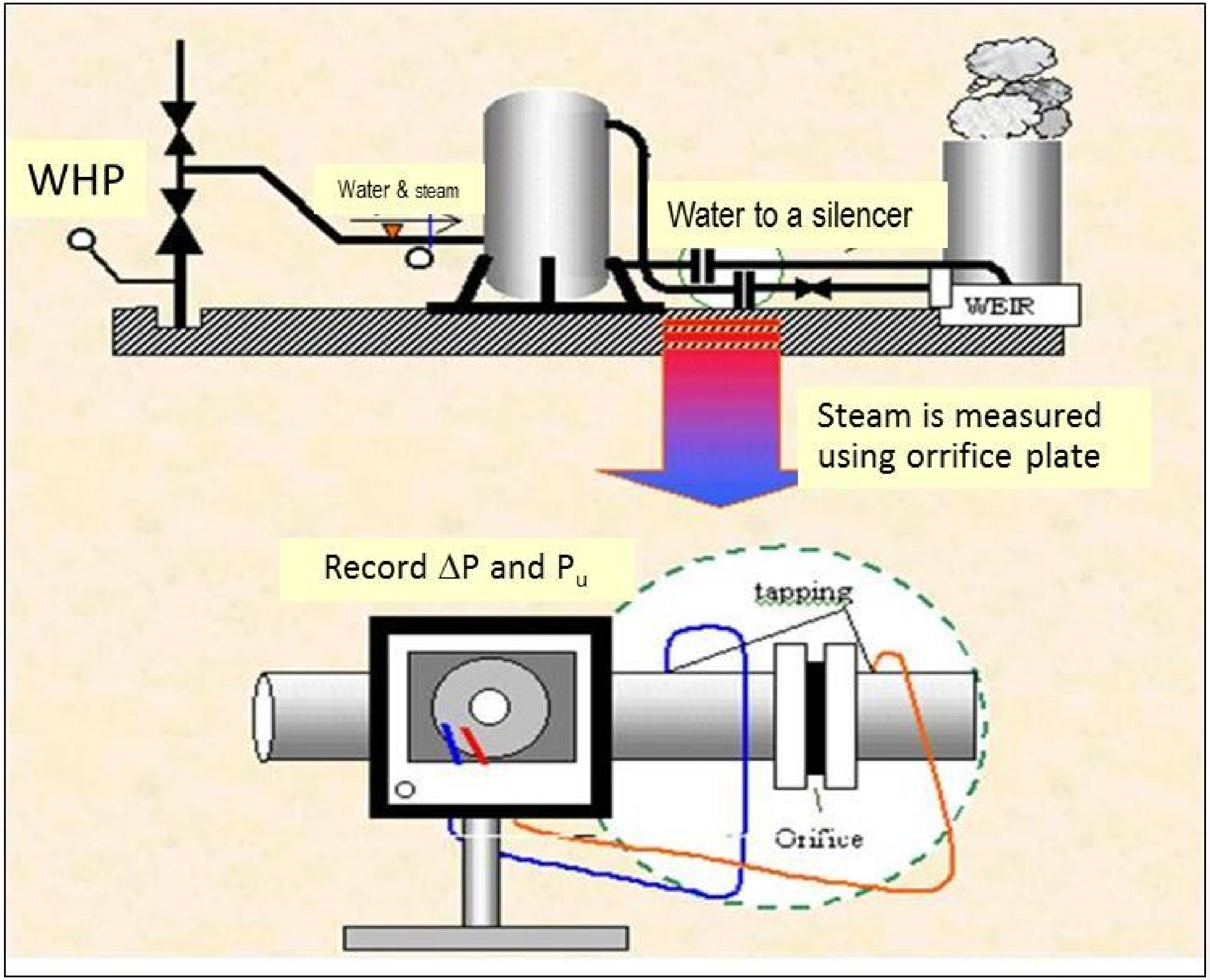
The most accurate method for measuring two-phase flows from geothermal wells is to use an efficient cyclone separator (Bangma, 1961).



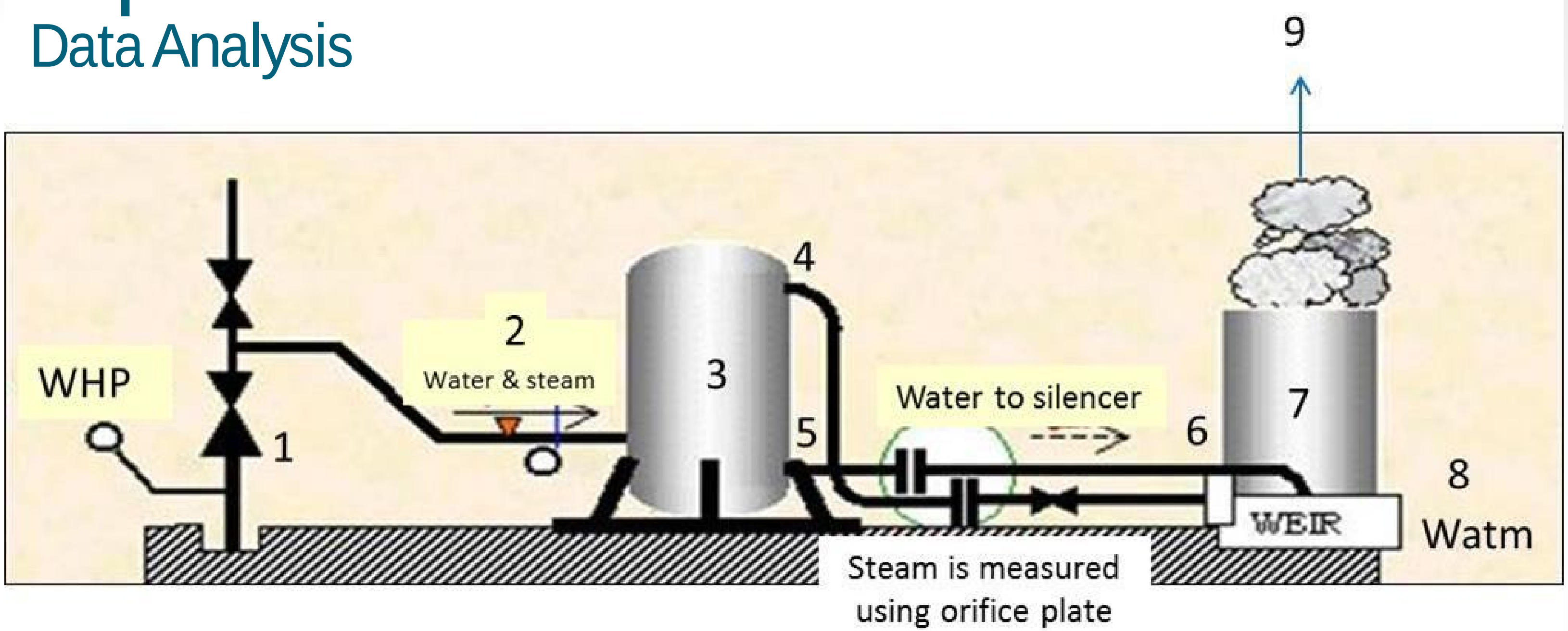
The separator method separates the steam and water phases, allowing their individual measurement. Both phases measurement using orifice flow meter

Separator Method

Measurement of steam using orifice plate and water using weir box



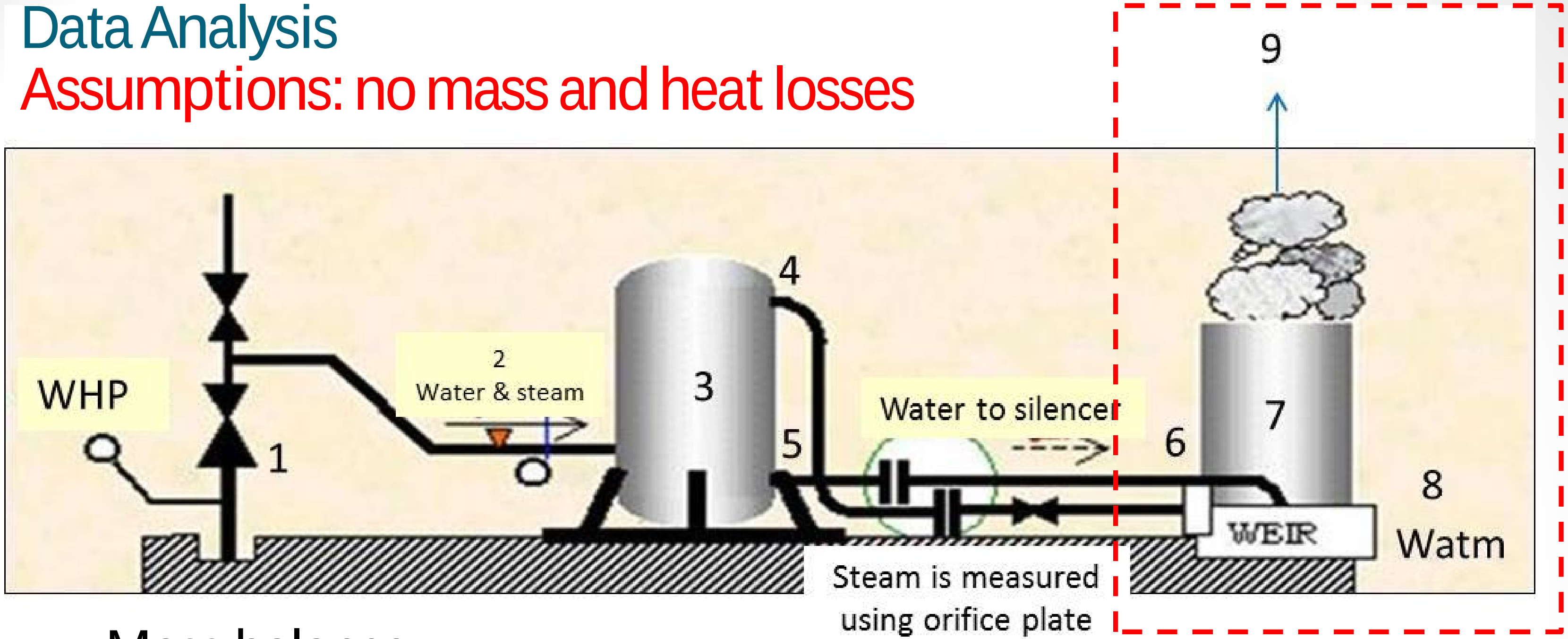
Separator Method
Data Analysis



- Well Head Pressure (WHP) : P_1
- Separator Pressure : P_3
- Silencer Pressure : P_7
- Fluid from wellhead: m_1, h_1
- Fluid enter the separator: m_2, h_2
- Steam from separator: m_4, h_4
- Water from separator flow to a silencer: m_5, h_5
- Water enter the silencer: m_6, h_6

Data Analysis

Assumptions: no mass and heat losses



- Mass balance:

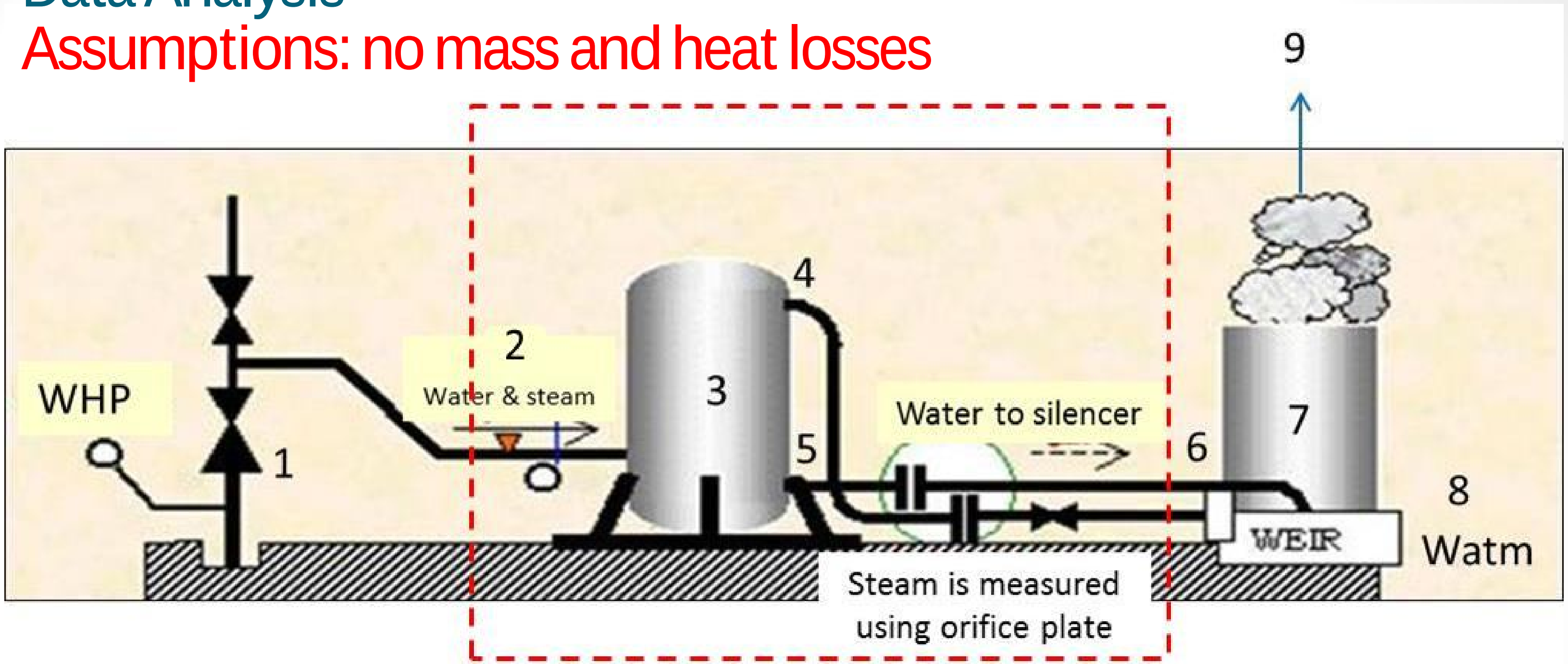
  $m_6 = m_7 = W_{atm} + m_9$
- Assumption: 5 ➔ 6 no mass and heat losses. $h_5 = h_6$
- Enthalpy of water into silencer (h_6) = $h_{f@separator\ pressure}$
- h_f, h_{fg} at silencer pressure: h_{f7}, h_{fg7} (From Steam Table)
- Steam fraction in the silencer $X_7 = (h_6 - h_{f7})/h_{fg7}$
- Mass flow rate of steam out from silencer:

  $X_7 = m_9/(m_9 + W_{atm})$ ➔ $m_9 = \ldots$
- Mass flow rate of water flow into the silencer (m_6)

  $m_6 = W_{atm} + m_9$

Data Analysis

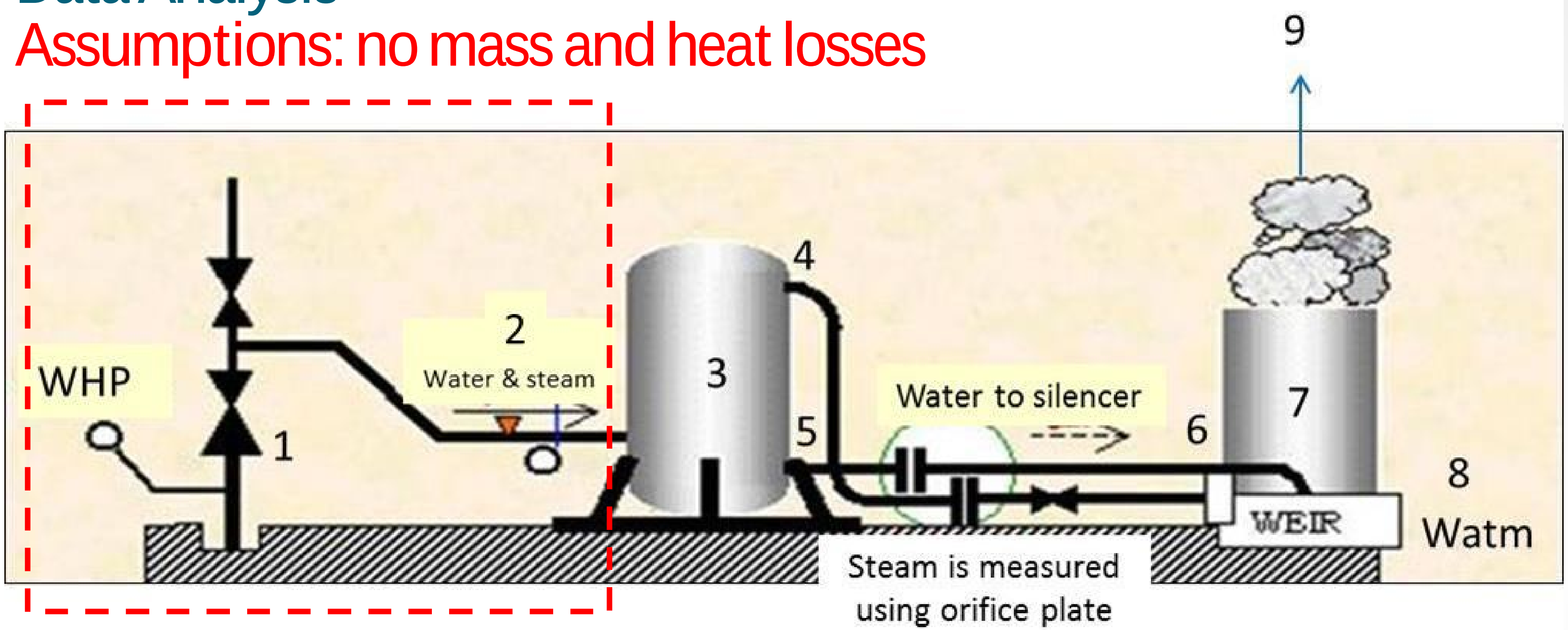
Assumptions: no mass and heat losses



- Mass flow rate of water flow into the silencer = $m_5 = m_6$
- Mass flow rate of steam from separator is measured using orifice plate = m_4
- Mass balance: $m_3 = m_4 + m_5 = m_2$
- Steam fraction in the separator: $x_3 = m_4/(m_4+m_5)$
- h_f, h_{fg} at separator pressure: h_{f3}, h_{fg3}
- Enthalpy of fluid at separator pressure

$$h_2 = h_{f3} + x_3 \, h_{fg3}$$

Data Analysis
Assumptions: no mass and heat losses



- Mass flow rate of water at the wellhead = $m_1 = m_2$
- Assumption: 1 ➔ 2 no mass and heat losses. $h_1 = h_2$
- h_f, h_{fg} at wellhead pressure: h_{f1}, h_{fg1}
- Enthalpy of fluid at wellhead pressure

$$h_1 = h_2 = h_{f1} + x_1 h_{fg1} \Rightarrow X_1 = (h_1 - h_{f1})/h_{fg1}$$

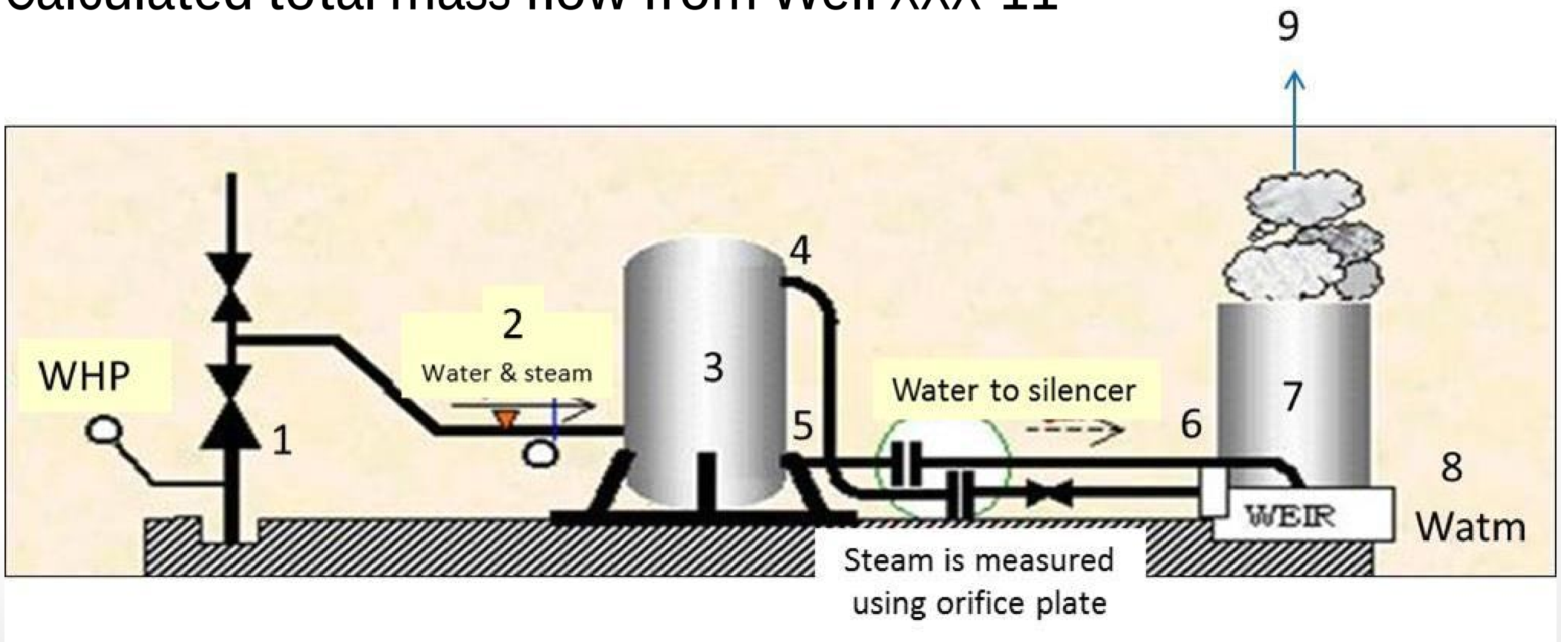
Excercise

Flow Measurements & Production Testing

Exercise -1
Well testing using orifice plate and weir box

During a well test, at wellhead pressure of 20.9 barg, fluid from Well XXX-11 is flowed into a separator and separated at 9.2 barg pressure. Water from the separator is flowed into a silencer and measured using a weir box (at atmospheric pressure). The water flow rate from weir box is 173 ton/hour. Steam from separator, as measured using orifice plate, is 27.2 ton/hour

Calculated total mass flow from Well XXX-11



Excercise - 2
Well testing using Separator Method (orifice)

An output test is done on Well ITB 12 using separator (steam and water measurement using specific orifice), with the results shown in this table below. Calculate the discharge enthalpy and total mass flow. Plot the enthalpy and mass flow against the WHP (for deliverability curve).

The data are:

Orifice Radius

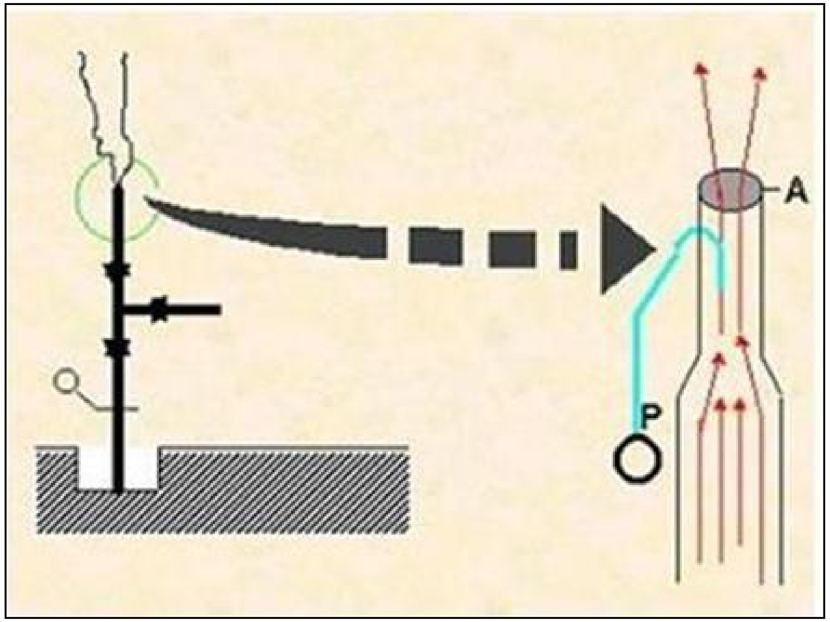
Inside diameter (ID) Pipe, P = 14” mild steel

Orifice diameter, d = 6.625” mild steel

WHP [bara]	P. Separator [bara]	P. Steam [bara]	∆P.steam [bar]	T.W [C]	∆P.water [bar]
8	7.6	7	1.688	168	0.536
8.2	7.6	7.2	1.546	168	0.519
9.7	9.6	9.3	0.674	178	0.416
11.7	11.5	11.5	0.290	186	0.275
12.7	12.9	12.9	0.161	191	0.202
15.1	14.8	14.7	0.069	197	0.111
16.4	16.2	16.2	0.028	202	0.040

Excercise - 3
Well testing - Lip Pressure Method Vertical Discharge

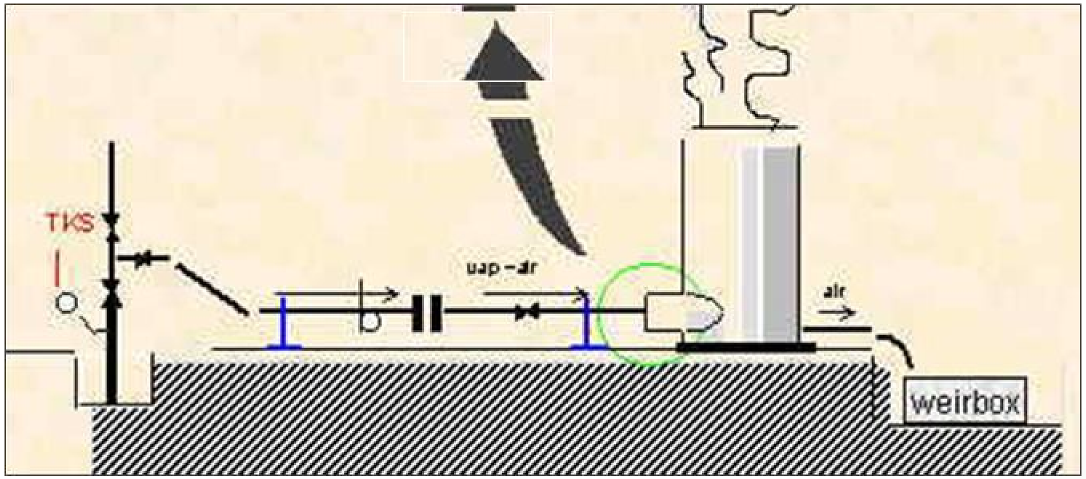
Production testing is conducted using lip pressure vertical discharge for 3 hours using a 153 mm diameter lip pipe. Pressure gauge shows that the wellhead pressure is 25 barg while lip pressure is 3.25 barg. Completion of the test results is estimated the feed zones at depth of 1323 m and the temperature 230ºC. If at feed zone depth consist of only one phase, saturated liquid, determine flowing enthalpy, total mass flow rate and potential electric well (if conversion factor is 0.1) !.



Exercise – 4
Well testing using lip pressure Method
Horizontal discharge

Production testing for ITB 14 Well using Lip pressure. Fluid from the well discharged horizontal to silencer with lip pipe (diameter 203 mm). Water from silencer measured using V-notch 90^o weir box. Data from the measurement results shown in this table below. Plot deliverability curve.

		Test 1	Test 2	Test 3	Test 4	Test 5
WHP	[bara]	16.5	19.6	24.2	26.6	29
Water level di weir box	[mm]	325	310	290	266	222
Lip Pressure	[bara]	5.2	4.65	3.75	2.93	1.79



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Terimakasih