Department of Geoscience and Petroleum

Examination paper for TPG4230 Field Development and Operations

Academic contact during examination: Milan Stanko

Phone: +47 954 40 756

Examination date: 09.08.2018

Examination time (from-to): 09:00 – 13:00

Permitted examination support material: D: No printed or hand-written support material is allowed. A specific basic calculator is allowed.

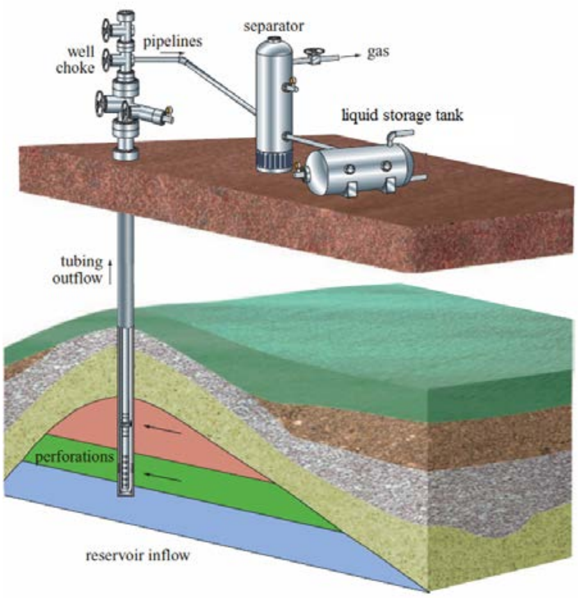
Other information:

Language: English

Number of pages (front page excluded):

PROBLEM 1 – Small gas field planning

Atoka is a small sandstone reservoir bearing dry gas located in Pittsburg County, Oklahoma. The initial gas in place is 2.5 E9 Sm^3 and with an initial reservoir pressure of p_i = 140 bara. The reservoir is planned to be developed and produced by the company Paleo Inc. **with standalone vertical wells** (each one with its own separator as shown in the figure below).



The wells will have an average depth of 3200 m and completed with a 4 inch production casing and 2 3/8 inch production tubing, and gas is produced through the tubing. The wells will be equipped with an adjustable wellhead choke. The separators operate with a constant pressure of 4 bar.

Paleo Inc. is currently in negotiations to supply the nearby Tenaska Kiamich power generating station with total constant gas rate of 320 000 Sm^3/d for a minimum period of 4 years. The power company is afraid of mounting gas prices in the US and is proposing a fixed price of 3 USD per thousand standard cubic feet for the whole period (1000 scf = 28.3168 Sm^3).

You are an engineer hired by Paleo Inc. to perform field development studies on the Atoka reservoir. You will have to determine how many wells are necessary to deliver the 4 year plateau rate to the power company and will perform NPV calculations to assess the profitability of the project. The tasks and data necessary to perform your calculations are detailed next.

Useful information

G, initial gas in place	2.5E+9	Sm^3
p_i, initial reservoir pressure	140	bara
C_R, inflow	48	$Sm^3/d/bar^{2n}$
n, inflow	0.8	
C_T, Tubing coefficient	3.50E+03	Sm^3/bar
S, tubing	0.37	
Sep pressure	4	bara
Number of operational days in a year	350	

Material balance:

$$p_R = p_i \cdot \left(1 - \frac{G_p}{G}\right)$$

Inflow equation:

$$q_g = C_R \cdot \left(p_R^2 - p_{wf}^2\right)^n$$

Tubing equation:

$$q_{gsc} = C_T \cdot \left(\frac{p_{wf}^2}{e^S} - p_{wh}^2\right)^{0.5}$$

-Assume all wells will perform identically.
-Consider only dry gas flow in reservoir and in tubing. Assume that the wellhead is very close to the separator thus the pressure downstream the choke can be assumed as equal to separator pressure.
-If you wish to perform plateau calculations to solve this exercise, do them in a year basis, where the year number represents the end of the year. Production starts at the end of year “1” (year 1 is when capex is spent and wells are drilled). To calculate cumulative production at any given year, assume the production at the end of the previous year remains constant through the year.
-DRILLEX: 2 E6 USD per well. All wells will be drilled in the first year.
-OPEX: 0.5 E6 USD per year. Assume this number constant with time.
-CAPEX: 1 E6 USD. All CAPEX is paid in the first year.
-Discount rate (for NPV calculations): 8%
-The formula for NPV:
NPV = {\sum_{t=0}^{N} R_t \over (1+i)^{t} }
Where:
-t is the year counter
-N is the total number of years
-R_t is the cash flow of year "t"
-i is the discount factor (in fraction)

TASKS

Task 1.a -What is the minimum number of wells required to deliver the plateau rate for a period of at least 4 years?
Solution:
4 wells are necessary to deliver the plateau rate of 3.2 E5 Sm^3/d for 4 years
Task 1.b-Explain how you have performed task 1.a
Solution:
We calculate cumulative production after a plateau production of 6 years:

$$G_p = q_{plateau} \cdot 4 \cdot 350 = 4.48E8\ Sm^3$$

Calculate reservoir pressure at that cumulative production

$$p_R = p_i \cdot \left(1 - \frac{G_p}{G}\right) = 140 \cdot \left(1 - \frac{4.48E8}{2.5E9}\right) = 114.9\ bara$$

With p_R, assume number of wells and calculate dp choke:
For Nwells = 1 : qwell = 3.2E5 Sm^3/d

-Compute pwf (IPR equation) = not physically possible!
For Nwells=2, q well = 1.6E5 Sm^3/d
-Compute pwf (IPR equation) = not physically possible!
For Nwells=3, q well = 1.06 E5 Sm^3/d
-Compute pwf (IPR equation) = not physically possible!
For Nwells=4, q well = 8 E4 Sm^3/d
-Compute pwf (IPR equation) = 50.6 bara
-compute pwh (tubing equation) = 35.3 bara
-compute DP choke = 31 bara

Task 2.a-What is the single well equilibrium rate (in Sm^3/d) when reservoir pressure is 95 bara and fully open choke.
Solution:
6.67 E4 Sm^3/d
Task 2.b-Explain how you have performed task 2.a
Solution:
Pwh = 4 bara (fully open choke)
From tubing equation, substitute pwf in ipr equation

$$q_g = C_T \cdot \left(\frac{p_{wf}^2}{e^S} - p_{wh}^2 \right)^{0.5}$$

$$p_{wf}^2 = e^S \cdot \left(\left(\frac{q_g}{C_T} \right)^2 + p_{wh}^2 \right)$$

$$q_g = C_R \cdot \left(p_R^2 - p_{wf}^2 \right)^n$$

$$q_g = C_R \cdot \left(p_R^2 - e^S \cdot \left(\left(\frac{q_g}{C_T} \right)^2 + p_{wh}^2 \right) \right)^n$$

We move all terms to the left side

$$\left(\frac{q_g}{C_R} \right)^{\frac{1}{n}} - p_R^2 + e^S \cdot \left(\left(\frac{q_g}{C_T} \right)^2 + p_{wh}^2 \right) = 0$$

The solution to this equation was found by trial and error. It is the number provided above.

Task 3.a-Perform NPV calculations from project startup until the end of 4 years of production in plateau mode (5 years in total). What is the NPV of the project (in million dollars of year 0?):
Solution:
NPV = 26.5 million USD

Task 3.b-Explain how you have performed task 3.a

Task 3							
Discount rate	[%]	8					
Gas price	[USD/1000 scf]	3					
End of year	gas production	Revenue	CAPEX	DRILLEX	OPEX	Cashflow	DCF
[years]	[Sm^3]	[USD]	[USD]	[USD]	[USD]	[USD]	[USD]
1	0.0E+00	0.0E+00	1.0E+06	8.0E+06	0.0E+00	-9.0E+06	-8.3E+06
2	1.1E+08	1.2E+07	0.0E+00	0.0E+00	5.0E+05	1.1E+07	9.7E+06
3	1.1E+08	1.2E+07	0.0E+00	0.0E+00	5.0E+05	1.1E+07	9.0E+06
4	1.1E+08	1.2E+07	0.0E+00	0.0E+00	5.0E+05	1.1E+07	8.4E+06
5	1.1E+08	1.2E+07	0.0E+00	0.0E+00	5.0E+05	1.1E+07	7.7E+06
							2.65E+07

Task 4.a-The field is planned to be abandoned when total field production drops to 80 E3 Sm^3/d (with fully open choke). What would be reservoir pressure (in bara) and recovery factor (in fraction) at abandonment?.

Solution:

pR = 44.19 bara

RF = 0.68

Task 4.b-Explain how you have performed task 4.a.

Solution:

Field rate 80e3 Sm^3/d and 4 wells gives well rate 20 E3 Sm^3/d

With tubing equation, q=20E3 Sm^3/d and pwh = 4 bara calculate bottomhole pressure: 8.39 bara

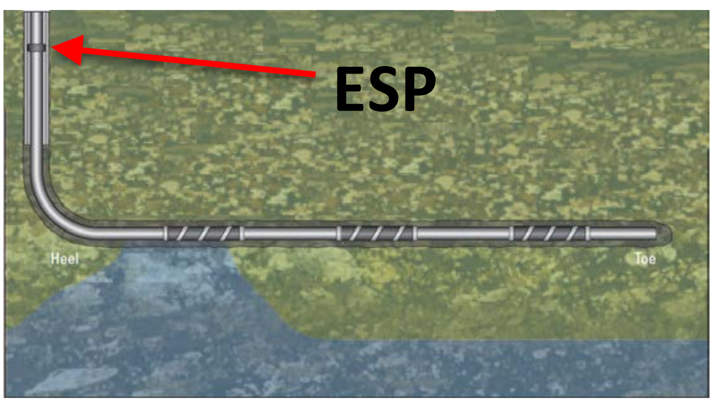
With IPr equation, q= 20E3 Sm^3/d and pwf = 8.39 bara, pR = 44.19 bara

With the material balance equation, pi = 140 bara, RF = 0.68.

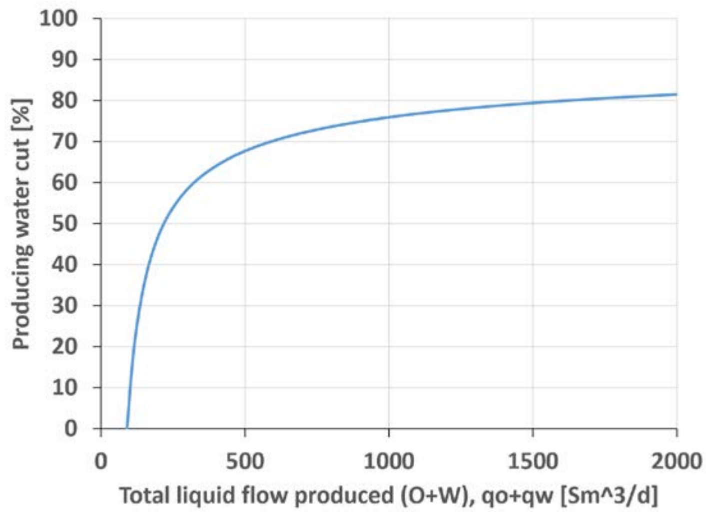
Problem 2 – Estimation and verification of ESP requirements

The Rio Ariari complex is a field currently under development in the region of “Los llanos” in Colombia. The reservoir has a thin layer (19 m) containing undersaturated oil and a very strong bottom aquifer.

The field will be produced with ESP-lifted horizontal wells like the one shown in the figure below.



Due to the presence of the aquifer, there is coning from the water layer into the well. Moreover, the producing watercut of the well is a function of the total liquid rate being produced from the well according to the following plot.



The Woodgroup company has proposed a unique ESP model (TE7000) with 50 stages which they claim has a wide operational envelope to handle all possible well operational conditions. Your task is to estimate and verify the ESP requirements for a well in the Ariari Field.

Useful information

-Neglect the flow pressure drop from the bottom-hole to the pump suction (i.e. $p_{suc} = p_{wf}$).

-Assume that the oil compressibility and GOR can be neglected such as the rate at standard conditions is equal to the rate at local conditions p and T.

-The Water cut (WC) is defined as

$$WC = \frac{q_{\overline{w}}}{q_{\overline{o}} + q_{\overline{w}}}$$

-The well inflow can be represented with a linear PI equation:

$$q = J \cdot \left(p_R - p_{wf}\right)$$

Where:

q……total liquid rate in Sm^3/d

J……productivity index for total liquid flow **[100 $Sm^3/d/bar$]**,

p_R…...reservoir pressure [**82.7 bara**]

p_{wf}…..bottom-hole flowing pressure [bara]

-Assume that the tubing from pump discharge to the wellhead is exactly vertical, with a length of 1000 m, and the pressure drop in the tubing can be calculated with the following equation:

$$p_{dis} = p_{wh} + \frac{h \cdot \rho_m \cdot g}{1E5} + 7.98E-15 \cdot \rho_m^{\ 0.828} \cdot q^{1.656} \cdot h \cdot d^{-4.484} \cdot \mu_m^{\ 0.172}$$

Where:

p_{dis} is the ESP discharge pressure, [bara]

p_{wh} is the wellhead pressure, [**40 bara**]

ρ_m is the oil-water mixture density, [kg/m^3]

g is the gravitational acceleration, 9.81 m/s^2

h is the vertical distance between ESP discharge and wellhead (**1000 m**).
q is the total liquid rate circulating in the tubing [Sm^3/d]
d is the internal pipe diameter [3 in = 0.076 m]
μ_m is the oil-water mixture viscosity [Pa s]
-The density of the oil water mixture is calculated using the following expression:
$$\rho_m = WC \cdot \rho_w + (1 - WC) \cdot \rho_o$$
Where the water density is 1025 kg/m^3
The oil density is 897 kg/m^3
- The oil+water mixture exhibits an emulsion behavior where its viscosity is a function of the water volume fraction. The cutoff watercut is 60%.

Regime	Richardson emulsion viscosity
Oil continuous (WC < 60%)	$\mu_m = \mu_o \cdot e^{3.215 \cdot WC}$
Water continuous (WC > 60%)	$\mu_m = \mu_w \cdot e^{3.089 \cdot (1 - WC)}$

The viscosity of the oil is 10 cp and viscosity of the water is 1 cp (1 cp = 1 E-3 Pa s)

-The pump power [in watts, W] can be estimated with:
$$Power = \frac{q \cdot \Delta p \cdot 1E5}{\eta \cdot 24 \cdot 3600}$$
Where Δp [bara], q in [m^3/d]. Assume a constant pump efficiency (η) of 0.6.

-The pump head [m] is
$$\Delta h = \frac{\Delta p \cdot 10^5}{\rho_m \cdot g}$$
Where Δp [bara], ρ_m [kg/m^3] and g = 9.81 [m/s^2]

TASKS:
Your tasks are:

Task 5.a-What is the effective viscosity (in cp) of the oil-water mixture (using the Richardson equation) when the well is producing 250 Sm^3/d and 750 Sm^3/d?
Solution:
56.75 cp
2.3 cp

Task 5.b-Explain how you have performed task 5.a
Solution:
From the coning plot, at 250 Sm^3/d and 750 Sm^3/d the WC is 0.54 and 0.73 respectively. With WC, viscosities of the fluids and the Richardson equation the mixture viscosity is 56.75 cp and 2.30 cp respectively.

Task 6.a. -For the total liquid rates of 250 Sm^3/d, 750 Sm^3/d estimate the required pump pressure boost (DP in bar, input a positive number) and pump power (in kW) to deliver the rate if the wellhead pressure is constant and equal to 40 bara.
Solution:

Rate: 250 Sm^3/d:
DP = 55.9 bar
Pump power = 26.94 kW

750 Sm^3/d
DP = 67.0 bar
Pump power = 96.85 kW

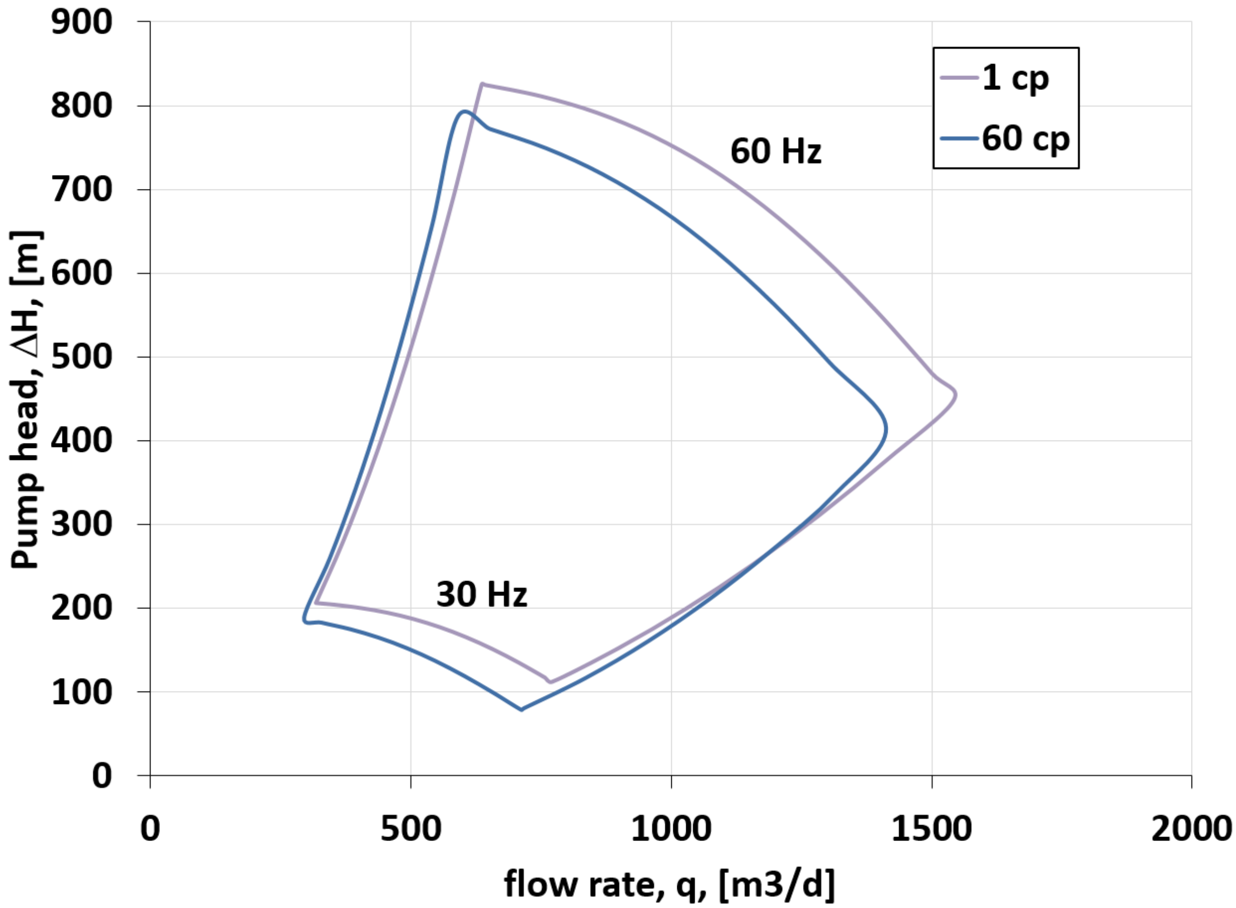
Task 6.b – Explain how you have performed task 6.a
Solution:
Rate: 250 Sm^3/d:
Using the ipr equation: pwf = 80.2 bara.
The mixture density is 966 kg/m^3
Using the equation provided with pwh = 40 bara

$$p_{dis} = p_{wh} + \frac{h \cdot \rho_m \cdot g}{1E5} + 7.98E-15 \cdot \rho_m^{\ 0.828} \cdot q^{1.656} \cdot h \cdot d^{-4.484} \cdot \mu_m^{\ 0.172}$$

Pdis = 136.2 bara
This gives a DP of = 55.9 bar
Pump power = 26.94 kW

Similarly for 750 Sm^3/d
Denm = 990 kg/m^3.
Pwf= 75.2 bara
Pdis = 142.2 bara
DP = 67.0 bar
Pump power = 96.85 kW

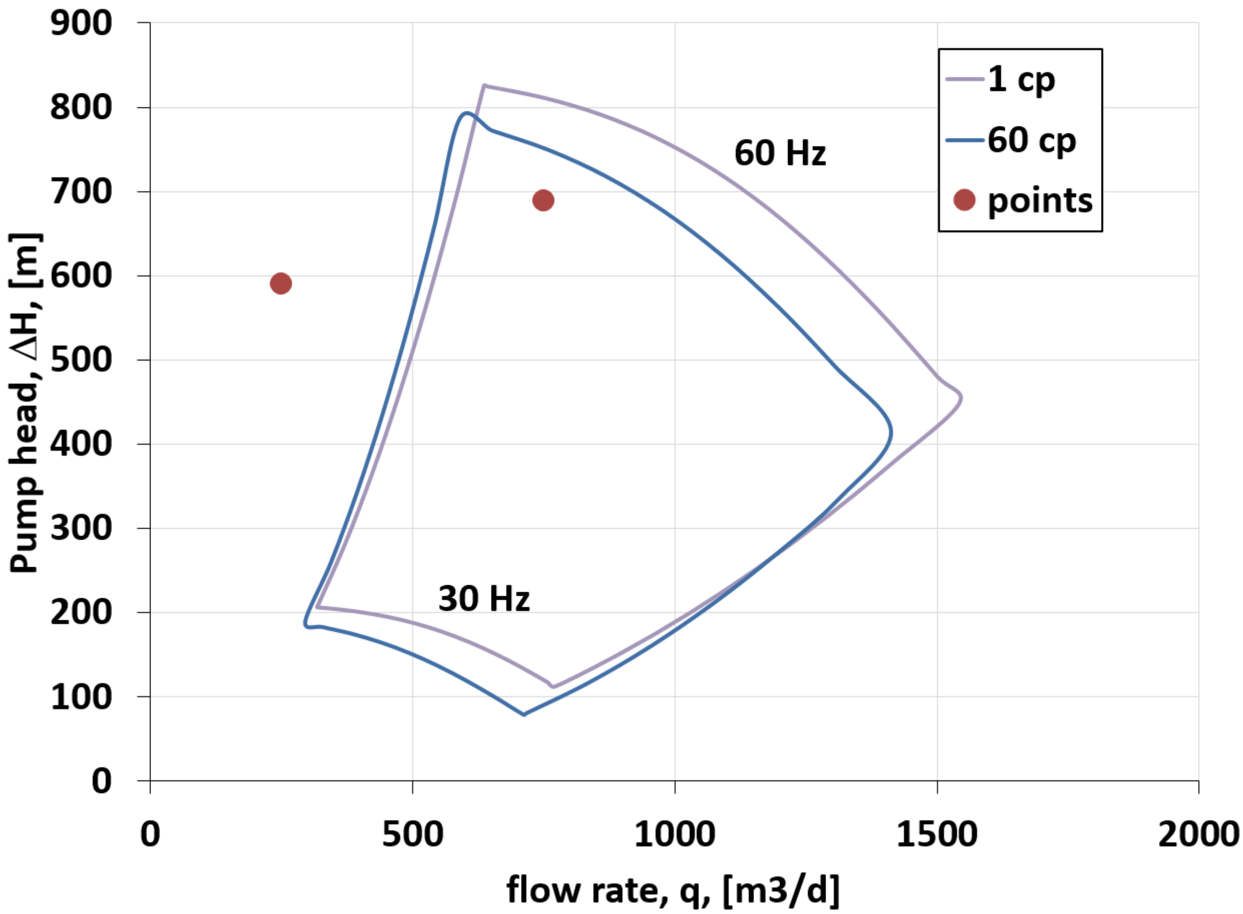
Task 7.-a -According to the ESP envelope given below, will the ESP model suggested be able to deliver the desired rate for 250 Sm^3/d and 750 Sm^3/d?



Solution:
No for 250 Sm^3/d
Yes for 750 Sm^3/d

Task 7.b- Explain how you have performed task 7.a. Provide an explanation based on physics of why the ESP operational envelope looks like the figure shows and what happens with ESP performance with viscosity.

Solution:
For 250 Sm^3/d the pump head is:
DH = 590 m. Thus it is below the minimum flow rate line
For 750 Sm^3/d the pump head is 689 m, thus It falls inside the envelope



AUXILIARY DERIVATIONS:

$$p_{in} = p_{out} + \frac{h \cdot \rho_m \cdot g}{1E5} + \frac{f}{1E5}\frac{h}{d} \cdot \rho_m \cdot \frac{q^2}{2 \cdot \pi^2 \cdot \frac{d^4}{16}}$$

$$f = 0.16 \cdot \left(\rho_m \cdot \frac{q^2}{\pi^2 \cdot \frac{d^4}{16}} \cdot \frac{d}{\mu_m} \right)^{-0.172}$$

$$p_{in} = p_{out} + \frac{h \cdot \rho_m \cdot g}{1E5} + 0.16 \cdot \left(\rho_m \cdot \frac{q^2}{\pi^2 \cdot d^3} \cdot \frac{16}{\mu_m} \right)^{-0.172} \frac{8 \cdot h}{\pi^2 \cdot 1E5 \cdot d^5} \cdot \rho_m \cdot q^2$$

$$p_{in} = p_{out} + \frac{h \cdot \rho_m \cdot g}{1E5} + 7.98E-15 \cdot \rho_m{}^{0.828} \cdot q^{1.656} \cdot h \cdot d^{-4.484} \cdot \mu_m{}^{0.172}$$