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OPTIMUM OPERATIONAL PRESSURE FOR A 55 MW TURBINE UTILIZED IN A WET STEAM FIELD

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Abstract

The objective of this work is to calculate the optimum pressures for the technical operation of a 55 MW double cylinder turbine in a tandem configuration using mass and energy balance equations, accompanied by a technical-economic study. The maximum dryness at the turbine outlet should be kept at 85 % and the power generation maintained constant. The values of the various calculated steam pressures were 10, 9, 8 and 7 bar and 3.5, 3.2, 2.5 and 2.0 bar, for the high and low steam pressures respectively, while at the turbine outlet the pressure was kept constant at 0.075 bar. The most important results obtained showed that, there were two pressures with the best performance : 9 bar and 3.2 of high and low steam pressure, respectively and 0.075 bar at the turbine outlet. Other relevant alternatives were also found.

Introduction:

CHARACTERISTICS OF THE GEOTHERMAL WELLS

The importance of a geothermal field, wet or dry (1) is based on 4 fundamental features: a source of natural heat of great output, an adequate water supply, an aquifer, or permeable reservoir rock, and a cap rock. Once these features are identified the evaluation of the reservoir is initiated by drilling wells, which are induced and integrated to the steam production system once the heat transfer through the well walls is aproximately constant.

After a well is activated, it is kept under production for a period of time and then its production curves are determined. These curves help in the analysis of the behaviour of the masic flow when the pressure head changes, which is very variable from well to well (83-28 bar). Cerro Prieto III (C P III) geothermal field has the highest recorded pressures.

The real operational conditions of a well difers from the ideal case pictured in the previous paragraphs in two main aspects:

a).-The production curves of a well vary with the lapse of time. Therefore the selection of an optimum high pressure is not recommended as the well will not flow when a change on the production curve is registered. For that reason, smaller pressures than the optimum are recommended.

b).-The hot brine submitted to several flashes to obtain steam becomes enriched in salts, which may produce scaling in the superficial equipment.

At C P II and C P III geothermal fields, a double flash system is utilized. Although it is obtainable a greater amount of available energy using this process, there are disadventages such as: a).-The secondary separator has a tendency to scale, b).-The production rate of low steam pressure to high steam pressure is very reduced (10 % of the total).

At the present time (2) C F E (Compañia Federal de electricidad), is carrying out a feasibility study and analysis to dispose of the second stage of flash (second separator). And where the case may be of a low pressure wellhead, to eliminate the first stage of flash (first separator).

OPTIMATIZATION OF GEOTHERMOELECTRIC PLANTS

The most important objective in planning a geothermoelectric plant is the conversion of calorific energy extracted from the reservoir, into mechanical energy to transform it in electricity, optimizing pressure parameters, steam flow and temperature, to be able to utilize the maximun available energy.

The geothermal field at C P is of the liquid dominant or wet steam type. For that reason the basic heat cycles applied to this type of resource have been selected : a).-Simple flash cycle (C P I) and b).-Double flash cycle (C P II and C P III) (Fig. 1).

At the geothermoelectric plants, the cost of steam transmission results as an addition to the cost of the installation of the plant. Thus, it is necessary to take into account the topographical conditions and the length of the transmission lines as much as the characteristics of the wells.

REAL BEHAVIOUR OF THE GEOTHERMAL FIELD

The information on the production of each well such as enthalpy, non-condensable gases content and the design of steam lines to the plant, among other variables, will be obtained at the begining of the project. However, many of these variables change with time and can not be predicted with accuracy; some of them may be mentioned :

a).-The global pressure of the reservoir will be diminishing according to the exploitation of the field,

b).-The permeability is reduced due to the formation of scaling in the reservoir, resulting in an irreversible reduction of the production of each well,

c).-Some wells are collapsed as a result of corrosion of their walls or else due to poor cementation which weakens the ademe.

d).-Variation of the non-condensable gases content in the mixture with time,

e).-Dragging of solid particles such as sand at high velocity in some producing wells.

BACK UP STEAM

The back up steam will substitute the missing steam which usually arrives to the turbine, due to any contingency or to a global reduction of the production. Based on that it will be necessary to consider the following aspects:

a)-Any producing well may fail due to collapsing. Thus, the importance of having in line a back up well,

b).-Any of the wells of the system may increase unexpectedly its non-condensable gases content. The reduction of the gas content is carried out by adequate mixing from several wells,

c).-The decline of the reservoir based on the loss of local production from each well, with an annual (3) decrease of 10 % of its global production,

In the preliminary studies for C P IV, the installation of a turbine as those already existing in C P II and C P III has been planned. According to the prefeasibility study (4, 5) carried out by C F E ,it has been indicated that the behaviour of the reservoir gave positive values showing that there is enough steam to generate 220 MW.

FLEXIBILIBILITY OF OPERATION OF THE TURBINE

1).-Higher admission pressure. If it is decided to operate the turbine at a higher pressure, the limit will be set by the design factors of the turbine shell. This increment in pressure, on the one hand, improves the unit thermal consumption of the plant (not so the internal efficiency of the turbine), but on the other, increases the humidity at the exit of the turbine causing a magnification of the erosion on the last blades of the turbine.

2).-Smaller admission pressure. If by a prediction error the presssure of the reservoir diminishes beyond the anticipated and becomes necessary to operate the turbine at a smaller pressure, more steam than the initiallly required would be needed to produce the same power. The specific volume of the steam is bigger at a smaller pressure causing problems during the expansion of the steam inside the turbine. Therefore it is not possible to ignore the loss of pressure due to the exploitation of the reservoir with the lapse of time.

3.-Non-condensable gas content. If the volume of non-condensable gases increases beyond the limit set by the design of the turbine shell, it may cause serious problems to keep the vacuum at the condensers, thus diminishing the power of the turbine (6).

SEPARATION PRESSURE

With the information from the previous paragraphs the diameters and lengths of each pipeline branch and the mains are obtained. These are followed by the selection of various options to supply the plant with steam, varying the pressure of the wells as to obtain the nominal volume flow to the turbine inlet. With these supplying arrangement the pressure that may be associated to each separator is calculated. This is carried out by taking the turbine as the starting point, continuing up stream and ending at the wells . This process is not as simple as it looks, as it is necessary to iterate until the volume flow and the pressure of each pipeline branch coincide with the characteristic curve of the well.

METHOD OF CALCULATION

The double cylinder turbine in a tandem configuration which is the basis of this work is actually being used at C P II and C P III, has the following nominal operational conditions (Table I):

Table I.-Nominal operational conditions for the double cylinder tandem compound turbine.

An admission of high pressure steam.	10.50 bar man
An admission of low pressure steam.	3.41 bar man
Condenser maximum pressure	0.10 bar man
Nominal power at 100 % capacity	55,000 KW
High pressure steam flow	303,133 Kg/hr
Low pressure steam flow	68,883 Kg/hr

The thermodynamic properties associated to the described pressures at Table I were taken from Keenan et al (7).

Several thermodynamic equations for mass and energy balance were used to get specific results as follows:

a).-The turbine outlet enthalpy for the high pressure steam:

$$S_{gh} = S_{fo} + X_{oh} * S_{fgo}$$

$$X_{oh} = (S_{gh} - S_{fo})/ S_{fgo}$$

$$h_{oh} = h_{fo} + X_{ho} * h_{fgo}$$

b).-The turbine outlet enthalpy for the low pressure steam.

$$X_{ol} = S_{gl} - S_{fo})/ S_{fgo}$$

$$h_{ol} = h_{fo} + X_{ol} * h_{fgo}$$

c).-The outlet dryness of the mixture which is required to evaluate the efficiency of the turbine, as follows:

$$P = [M_h (h_{gh} - h_{oh}) + M_l (h_{gl} - h_{ol})] N$$

$$N = P / [M_h (h_{gh} - h_{oh}) + M_l (h_{gl} - h_{ol})$$

d).-The real outlet dryness and enthalpy are calculated for both stages, high and low pressure steam:

$$W_a = (h_{gh} - h_{oh}) N \quad W_l = (h_{gl} - h_{ol}) N$$

$$h_{orh} = (h_{gh} - W_h) \quad h_{orl} = (h_{gl} - W_l)$$

$$X_{orh}=(h_{orh}- h_{fo})/h_{fgo}$$

$$X_{orl}=(h_{orl}- h_{fo}) / h_{fgo}$$

e).-The real dryness at the turbine outlet with two steam admission pressures:

$$X_m = [X_{oh} (M_h) + X_{ol} (M_l)] / (M_h + M_l)$$

f).-With a constant efficiency and a generation of 55 MW, the mass flow at high and low steam pressure will vary:

$$M_l = [P / N - \{M_h * (W_h)\}] / W_l$$

g).-To obtain the useful energy for the turbine :

$$E = [M_h (W_h) + M_l (W_l)] / (M_h + M_l)$$

h).-The efficiency of high and low steam pressure:

$$R_h = P_h/ M_h \quad R_l = P_l/M_l$$

NOMENCLATURE

h_{gh} = inlet specific enthalpy (KJ/Kg)
S_{gh} = inlet specific entropy (KJ/Kg K)
h_{fl} = specific enthalpy (KJ/Kg)
h_{gl} = specific enthalpy (KJ/Kg)
h_{fgl} = specific enthalpy (KJ/Kg)
S_{fl} = specific entropy (KJ/Kg K)
S_{fgl} = specific entropy (KJ/Kg K)
P_0 = pressure (bar)
h_{fo} = specific enthalpy (KJ/Kg)
h_{fgo} = specific enthalpy (KJ/Kg)
h_{ol} = specific enthalpy of the mixture (KJ/Kg)
S_{fo} = specific entropy (KJ/Kg K)
P = power (MW)
N = efficiency (%)
W_h = turbine work by high pressure steam(KJ/Kg)
W_l = turbine work by low pressure steam (KJ/Kg)
X_{oh} = turbine outlet dryness from high steam pressure stage (%)
X_{ol} = turbine outlet dryness from low steam pressure stage (%)
X_m = mixture dryness from low and high steam pressure stages (%)

M_l = low steam pressure flow (ton/hr)
M_h = high steam pressure flow (ton/hr)
R_h = low steam pressure yield (MWhr/ton)
R_l = high steam pressure yield (MWhr/ton)
X_{rho} = mixture real dryness at the turbine outlet of the high pressure stage (%)
X_{rlo} = mixture real dryness at the turbine outlet of the low pressure stage(%)
X_{mhl} = mixture real dryness at the turbine outlet of the high and low steam pressure (%)
E = useful energy extracted by the turbine (Kj/Kg)
$\$_{sh}$ = high steam pressure cost (Dlls)
$\$_{sl}$ = low steam pressure cost (Dlls)
$\$_{st}$ = low and high (total) steam pressure cost (Dlls)

Subscripts

f refers to a property of liquid in equilibrium with vapor
g refers to a property of vapor in equilibrium with liquid
fg refers to a change by evaporation
l refers to low pressure steam
h refers to high pressure steam
o refers to the turbine outlet
r refers to real
t refers to total
s refers to steam

ECONOMIC ANALYSIS

The economic analysis of any project is a very important tool, as it is expected to give information of its rentabilitty coupled with a convenient technical design . In this part of the work an economic analysis will be made considering the optimum admission pressure values to the turbine calculated previously. The fundamental objective for each case under study will be to find out the cost of vapor once the operational conditions are specified.

It is necessary to consider that in order to generate one MW of electricity, steam is needed, as much as a costly equipmént to support the plant. In this perspective it is convenient to distribute the cost of steam on a percentage basis, taking into account the contribution of each element to the energy generation process. According to previous studies (8), 60 % of the cost of the generation of energy is assigned to the equipment and the rest (40 %) it is associated to the cost of steam production.

In the cost of the equipment all the expenditures in the plant are included, such as personnel salaries, maintenance, equipment depreciation,...,etc., whereas the cost of vapor includes wells drilling, steam transmission, pipelines, valves, separators, among others. At the present time the cost (10) of the MWhr at 1988 prices is \$15.55 Dlls.

Case 1.-Operation of the turbine with high and low steam pressure (nominal operational conditions, Table I)

The values of R_h for the turbine (10) are 0.152 MW/ton/hr and 0.106 MW/ton/hr of high and low steam pressure respectively. Therefore to calculate its yield, next relations are used:

For high steam pressure:

R_h = 0.1521 MW/ton/hr

$\$_h$ = 0.152 MWhr/ton * 15.15\$/MW

$\$_h$ = 2.31 \$/ton/hr

As the steam represents 40% of the cost of production for each MW-hr:

$\$_{sh}$ = 2.31 \$/ton/hr * 0.4

$\$_{sh}$ = 0.92 \$/ton/hr

For low steam pressure:

R_l = 0.106 MW/ton/hr

$\$_l$ = 0.106 MW/hr * 15.15 \$/MW

$\$_l$ = 1.605 \$/ton/hr

$\$_{sl}$ = 1.605 \$/ton/hr * 0.40

$\$_{sl}$ = 0.642 \$/ton/hr

To produce 55 MW-hr are required 303.12 ton/hr and 68.85 ton/hr of high and low steam pressure. The cost of generation of 55 MW-hr with these steam volume flows would be:

$\$_{sh}$ = 303.12 ton/hr * 0.891 \$/ton/hr
= 270 Dlls

$\$_{sl}$ = 68.85 ton/hr * 0.642 \$/ton/hr
= 44.2 Dlls

$\$_{st}$ = 270 + 44.2 = 314.22 Dlls.

In short, to produce 55 MW-hr the cost of high and low steam pressure necessary will be 314.22 Dlls, i.e., 5.71 Dlls/MW-hr.

Case 2.-Turbine in operation with a single admission steam pressure

According to the thermodynamic calculations the optimum pressure of operation of the turbine with a single admission steam pressure will be 8 bar and 0.075 bar at the outlet, therefore the cost of the steam will be given by :

To produce 55 MW-hr are necessary 353.43 ton/hr of high steam pressure with a thermal yield of R_h = 0.153,

$\$_{sh}$ = 0.812 $/ton/hr * 353.43 ton/hr

$\$_{sh}$ = 333.29 Dlls , in other terms

$\$_{sh}$ = 6.05 Dlls/MW-hr

Case 3.- Operation of a turbine with a high and low steam pressure .

As a result of thermodynamic analysis the optimum pressures of operation of the turbine with high and low admission steam pressure are 9 and 3.2 bar, respectively. Considering previous calculations the cost of the steam will be given taking into account the yields of high steam pressure (R_h = 0.151) and low steam pressure (R_l= 0.129).

For high steam pressure:

$\$_{sh}$ = 0.181 $/ton/hr

For low steam pressure:

$\$_{sl}$ = 0.739 $/ton/hr

Briefly, 288 ton/hr and 79.812 ton/hr of high and low steam pressure respectively are required to produced 55 MW-hr. Thus, the total production cost of that electricity generation will be:

$\$_{sh}$ = 288 ton/hr * 0.721 $/ton/hr
= 207.66 Dlls

$\$_{sl}$ = 79.812 ton/hr * 0.739 $/ton/hr
= 58.98 Dlls

$\$_{st}$ = 266.7 Dlls, in other terms,

$\$_{st}$ = 4.85 Dlls/MW-hr.

Once established the method of calculation, it becomes simpler to determine the cost of steam for different steam pressures. On the basis, it may be assumed that it costs the same to produce high steam pressure at 10, 9, 8 and 7 bar, as much as it will be the same cost to produce low steam pressure at 3.5, 3.2, 2.5 and 2 bar, establishing the comparison at each level of steam pressure. What varies will be the amount of steam required to produce 55 MW-hr of power, keeping a dryness of 85 % at the turbine outlet. This is observed graphically in Figs. 2 and 3.

From an analysis of Figs. 2 and 3 where the values of high and low steam mass flows, work produced , useful energy and total steam cost are shown, the figures for the obtention of the optimum pressure work of the turbine were selected: 9 and 3.2 bar of high and low steam pressures, respectively with an 0.075 turbine outlet steam pressure. With these combinations of pressures it is obtained the maximun amount of useful energy from the geothermal steam. This corresponds to a cost of steam equal to 266.7 Dlls to produce 55 MW-hr, i.e., 4.85 Dlls/MW-hr.

By the same token, a single admission high steam pressure was found to give the maximun useful energy from the geothermal steam : 8 bar of high steam pressure with an 0.075 turbine outlet steam pressure. This arrangement produces a cost of 333.3 Dlls for a total of 55 MW, i.e., 6.06 Dlls/MW-hr (Fig. 3).

CONCLUSIONS

It was concluded that the optimum steam pressures which allowed the extraction of the maximum amount of energy from the geothermal fluid are as follows:

a).-9 and 3.2 bar of high and low steam pressures and 0.075 bar of outlet turbine pressure.

b).-A more strict alternative is to completely eliminate the second stage of flash (secondary evaporator), i.e., the source of low steam pressure , leaving alone the stage of high steam pressure based on two reasons: 1-equipment maintenance, and 2.-minimum contribution of low steam pressure to the total steam mass flow. A high steam pressure of 8 bar was selected as the optimum with 0.075 bar as the outlet turbine pressure.

c).-In case of a strict reduction of the pressure wellhead, far below the separation pressure of the first separator, it has been recommended to eliminate the source of the high steam separator, leaving alone the secondary separator.

d).-The steam pressure selections were made considering the more profitable technical economic-aspect of the project for the production of electricity.

e).-It is believed that the presures selected are the most appropiated for the real conditions of the Cerro Prieto geothermal field after 16 years of continuos exploitation.

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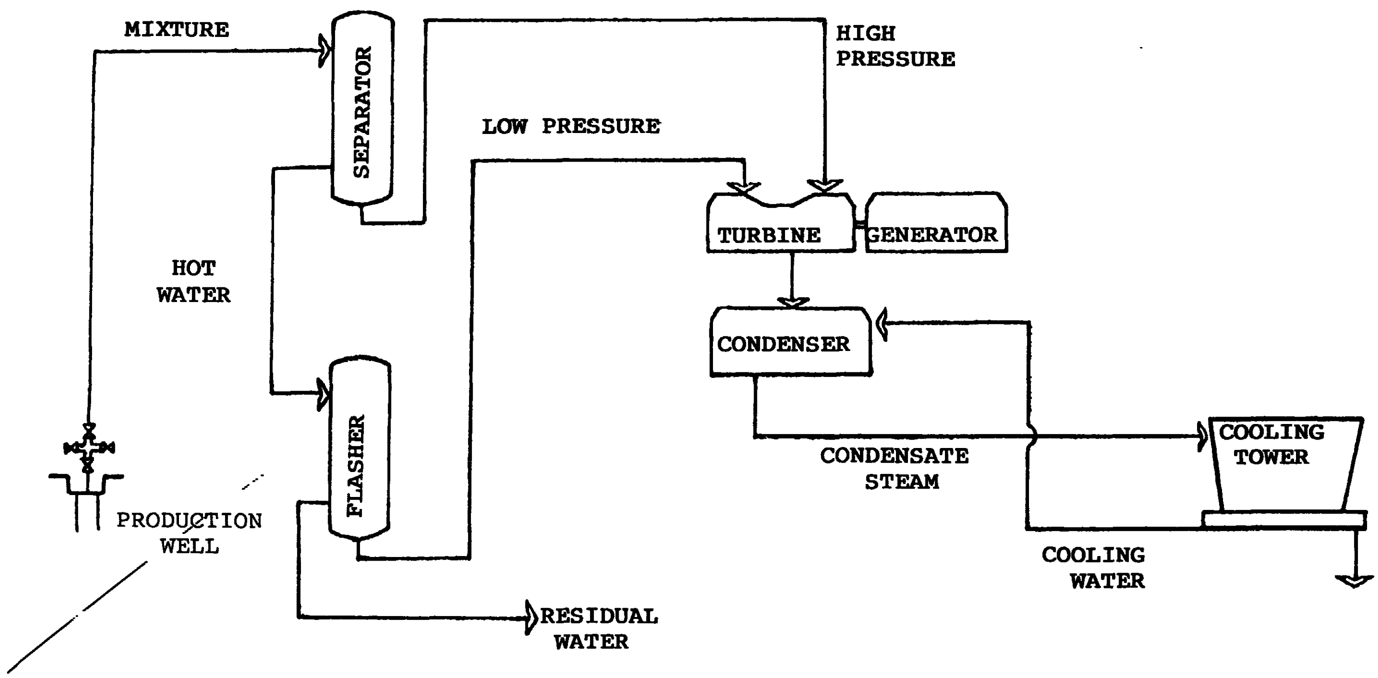

FIG. 1.- SEPARATED-STEAM/HOT-WATER-FLASH OR "DOUBLE FLASH" GEOTHERMAL POWER PLANT.

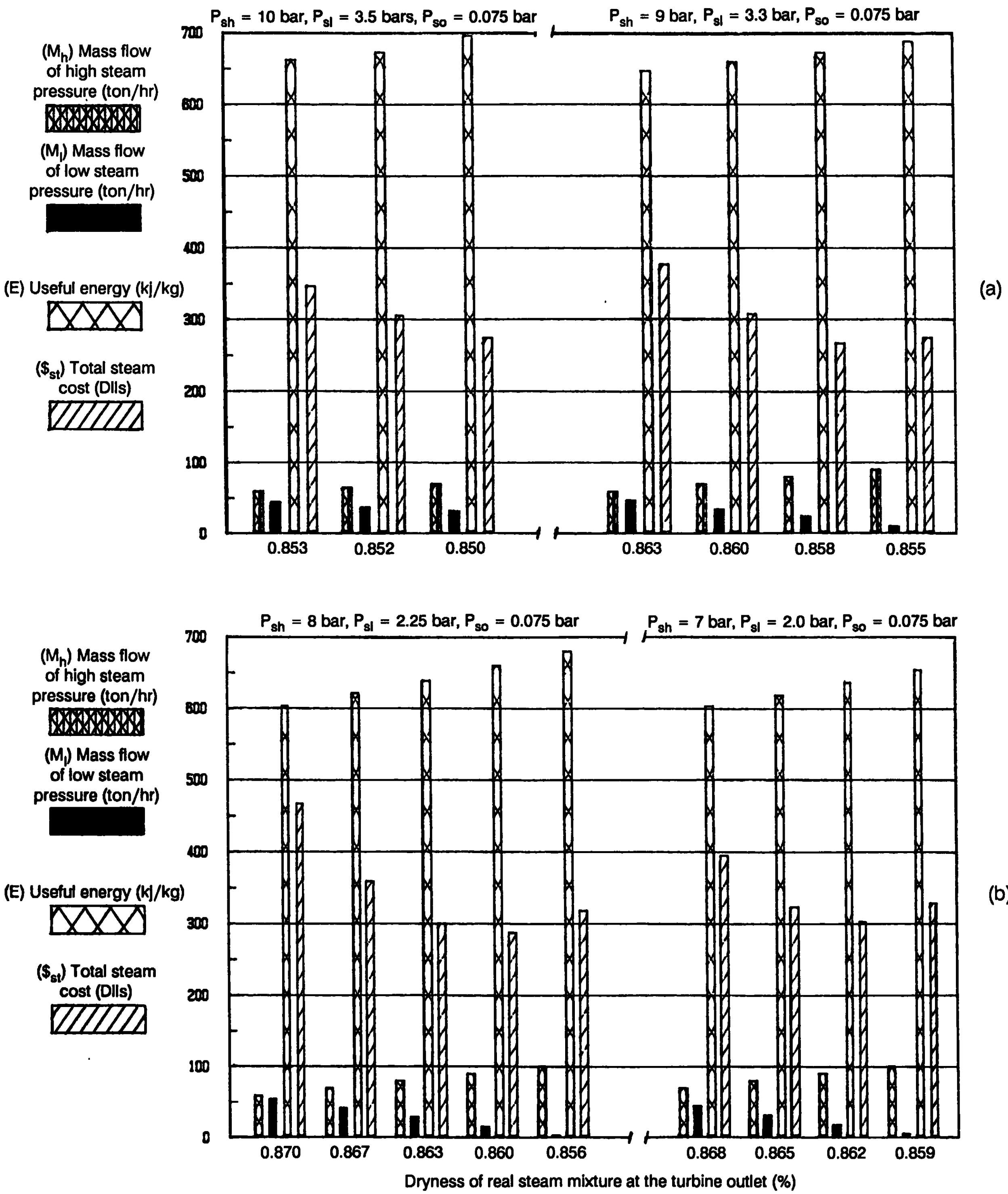

Fig.2 Analysis of dryness behaviour varying the high and low steam flows versus useful energy, total steam cost and mass flow.

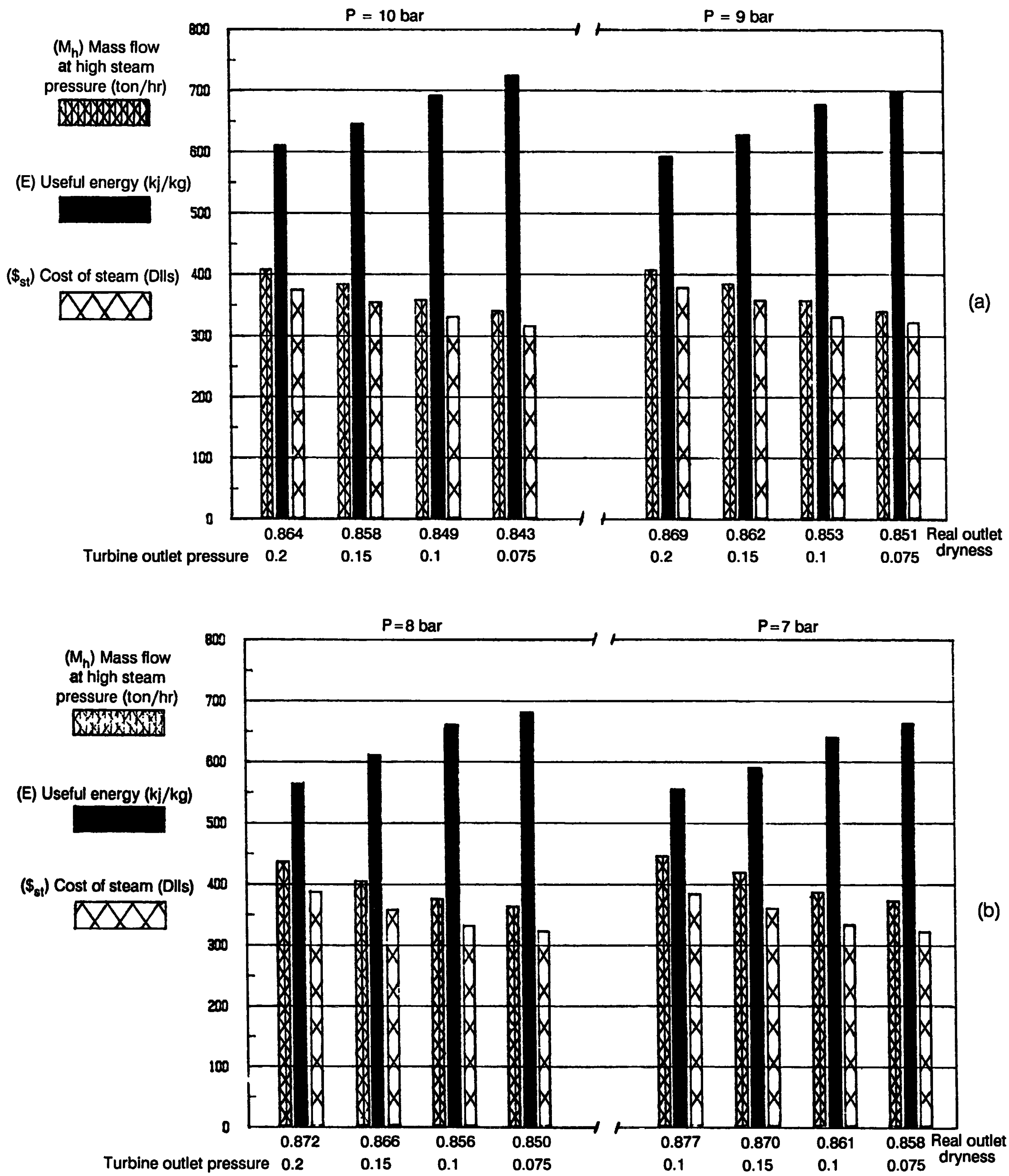

Fig. 3 Analysys of steam flow behavior during expansion versus useful energy, steam cost with single admission high steam pressure and mass flow.