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Steam Flow Balance in the Los Azufres Geothermal System, Mexico

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ABSTRACT

The results of a steam flow balance performed for the U-15 and U-16 electricity generation power in the Los Azfures geothermal system in February 2009 are presented in this paper. An ActiveX component *OrificeMeter* based on the ISO-5167-2 formulation for an orifice meter with D and D/2 tappings was used. The plant U-15 was fed by the production wells AZ-04, AZ-40, AZ-65D, AZ-69D; whereas AZ-28A, AZ-45, AZ-56, AZ-67 were connected to U-16. The analytical error is within ±4%.

The geothermal fluid is separated into vapor and liquid components at the wellhead. Thus, the conditions of temperature and pressure of steam at the well separator are along the saturation curve and the measurement of pressure or temperature is sufficient at the orifice meter of the well. However, there is a need to measure temperature and pressure at the production units. Similarly, the measurement of the pressure difference across the orifice plate is crucial. For example, an error of 0.002 m Hg-water column across the orifice plate of power plant U-15 or U-16 is equivalent to 1 ton/hr.

1. INTRODUCTION

Recently, the Comision Federal de Electricidad (CFE) initiated a project to rationalize and optimize the use of steam from the Los Azufres geothermal system for the generation of electricity. The Los Azufres system is located in the state of Michoacán, Mexico. The project included: a) the development of a numerical hydraulic model of the Los Azufres steam pipeline network (Garcia et al., 2008) and b) the installation of telemetric system to monitor the characteristics of production wells.

Presently, the telemetric system is in the state of installation and calibration. The system will continuously monitor the characteristics of production wells and the amount of steam received at each electricity generation power plant. We are also working to develop computer software which can be used to perform various calculations from the data monitored with the telemetric system. For example, an ActiveX component *OrificeMeter* based on the ISO-5167-2 formulation for an orifice meter with D and D/2 tappings is written in Visual Basic to calculate steam flow in a pipeline (Verma, 2009).

In this article, we present the application of *OrificeMeter* to perform the steam flow balance in two power plants (U-15 and U-16) in the Los Azufres geothermal system. A function *QmassOrificeMeter* is written in Visual Basic for Application (VBA) to calculate steam flow in a pipeline in an MS-Excel worksheet.

2. ORIFICE METER

Verma (2009) presented the derivation of a theoretical formula to measure fluid flow in a pipeline with an orifice meter with D and D/2 tapping. The formula was derived on the basis of continuity and the Bernoulli equations. The Bernoulli equation is only valid for incompressible fluids; therefore, the application of the theoretical formula to an orifice meter provides reasonable results for the determination of liquid flow.

The International Organization for Standardization (ISO) introduced some empirical parameters to the theoretical formula based on an extensive study comparing experimentally measured and theoretically calculated values of fluid flow (ISO, 2003). Thus, the empirical formula (ISO-5167-2) can be used to correctly calculate both liquid and vapor flow. The technical details and restrictions for the construction of orifice meter are also described in the ISO-5167-2 manual. Only the fluid flow calculation procedure will be discussed here, considering that the construction of orifice meters was performed according to the ISO-5167-2 specifications.

A schematic diagram of an orifice meter is presented in Figure 1. The ISO equation for mass flow rate Q_M is given as Equation 1:

$$Q_M = \frac{C}{\sqrt{\left(1-\beta^4\right)}}\frac{\pi}{4}\varepsilon d^2\sqrt{2\rho\Delta p} \tag{1}$$

Where ε and C are the given by the expressions in Equations 2 and 3:

$$\varepsilon = 1-\left(0.351+0.256\beta^4+0.93\beta^8\right)\left[1-\left(\frac{p_2}{p_1}\right)^{1/\kappa}\right] \tag{2}$$

$$\begin{aligned} C = {} & 0.5961+0.0261\beta^2-0.216\beta^8+0.00521\beta^{2.5}\left(\frac{10^6\beta}{\mathrm{Re}D}\right)^{0.7} \\ & +\left(0.0188+0.0063A\right)\beta^{3.5}\left(\frac{10^6}{\mathrm{Re}D}\right)^{0.3} \\ & +\left(0.043+0.080e^{-7L_1}\right)\left(1-0.11A\right)\frac{\beta^4}{1-\beta^4} \\ & -0.031\left(M_2-0.8M_2^{1.1}\right)\beta^{1.3} \end{aligned} \tag{3}$$

Where

A	$\left[=\left(\frac{19000\beta}{\mathrm{Re}D}\right)^{0.8}\right]$ (dimensionless)
D	internal diameter of pipe (m)
d	aperture of orifice plate (m)
l_1	upstream pressure tapping spacing from the upstream face (m)

L_1 $\left(=l_1/D\right)$ quotient of the distance of the upstream tapping from upstream face of the place and the pipe diameter (dimensionless)

l_2 downstream pressure tapping spacing from the downstream face (m)

L_2 $\left(=l_2/D\right)$ quotient of the distance of the downstream tapping from downstream face of the place and the pipe diameter (dimensionless)

M_2 $\left[=2L_2/(1-\beta)\right]$ (dimensionless)

p_1 pressure at the upstream tapping (Pa)

p_2 pressure at the downstream tapping (Pa)

Δp $(=p_1-p_2)$ pressure difference (Pa)

Q_M mass flow rate passing through the orifice plate (kg/s)

$\mathrm{Re}D$ $\left(=4Q_4/\pi\mu D\right)$ pipe Reynolds number at the upstream pressure tapping (dimensionless)

β $\left(=d/D\right)$ diameter ratio (dimensionless)

ρ Density of inflowing fluid (kg/m^3)

μ Dynamic viscosity of the inflowing fluid (Pa.s)

ε Expansibility factor (dimensionless)

κ Isentropic exponent (dimensionless). It is considered here as the ratio of the specific heat capacity at constant pressure to the specific heat capacity at constant volume.

When $D<0.07112\,\mathrm{m}$, the term $\left[+0.011(0.75-\beta)(2.8-D/0.0254)\right]$ is to be added to Equation 3.

There are various restrictions in the construction of an orifice meter (ISO, 2003). They are described here for easy use:

1. $0.05\,m \le D \le 1.0\,m$
2. $d \ge 0.0125\,m$
3. $0.1 \le \beta \le 0.75$
4. $0.9D \le l_1 \le 1.1D$
5. $0.48D \le (l_2+t_p) \le 0.52D$ for $\beta \le 0.6$
   $0.49D \le (l_2+t_p) \le 0.51D$ for $\beta > 0.6$
6. $\Delta p \le 0.25 p_1$
7. Check the value of pressure and temperature to satisfy the condition of steam region.

The following two restrictions for the value of Reynolds number are also mentioned in the ISO-5167-2 manual:

1. $\mathrm{Re}D \ge 5000$ for $\beta \le 0.56$
2. $\mathrm{Re}D \ge 16000\beta^2$ for $\beta > 0.56$

3. PROGRAM DESCRIPTION

The ActiveX *OrificeMeter* has nine write only properties: DPipe, dOrifice, tPlate, l1UpStream, l2DownStream, SepBoundary, TUpStream, PUpStream and delP. The properties are pipeline diameter, orifice aperture, orifice plate thickness, upstream pressure tapping spacing from the upstream face, downstream pressure tapping spacing from the downstream face, separation boundary for steam phase,

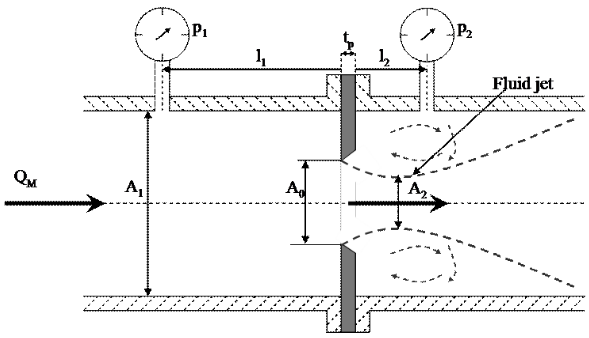

Figure 1: Schematic diagram of an orifice meter with D and D/2 tapping (after Verma, 2009). In the left side of orifice plate, the flow of steam is in whole pipeline; however, there is fluid (steam) jet near the plate on the right side, which is shown in the dashed curves. The turbulence due to jet is shown by the dashed curve arrows. A_1, A_0, and A_2 represent the area of pipeline, aperture of orifice plate, and the minimum area of the fluid jet, respectively.

pressure at the upstream tapping, temperature at the upstream tapping, and pressure difference between up- and down-stream tappings, respectively. SepBoundary values of 0, 1, 2 and 3 are used to calculate the flow in the superheated steam region, along sublimation curve, along liquid-vapor saturation, and along the critical isochors, respectively. Similarly, there are five read only properties: mass flowrate (QMass), volumetric flowrate (QVolume), number of iterations (NIteration), error number (NError) and warning number (NWarning).

In the geothermal industry, the orifice meters are constructed to meet ISO-5167-2 specifications; therefore, it is not a custom to provide the values of l_1, l_2 and t_p during the calculations. The program internally sets the values of l_1=D, l_2=D/2 and t_p=0.0, if the value of l_1 or l_2 is zero.

3.1 Using *OrificeMeter* in MS-Excel

Verma (2003) described in detail how to write a macro in a personal Excel workbook, which permits to use the macro in any workbook. The dynamic link library (“MyLib2009.DLL”) contains the objects *Steamtables* and *OrificeMeter*. *SteamTables* is used internally in the *OrificeMeter* to calculate the thermodynamic properties of steam. Verma (2008) described the registration procedure of DLL file in the Windows environment in order to use it in MS-Excel.

The listing of functions *QmassOrificeMeter* (DPipe, dOrif, tPlat, L1, L2, SepBndry, P, T, delP) is available from the authors for scientific use. The function arguments are inner diameter of pipeline, aperture of orifice plate, thickness of orifice plate, upstream pressure tapping spacing from the upstream face, downstream pressure tapping spacing from the downstream face, liquid-vapor separation boundary, upstream pressure, upstream temperature and up- and downstream pressure difference, respectively. If there is any error in the input data, the error number with a negative sign is assigned to the function. Similarly, the function values of -8 and -9 represent the two warnings associated with Reynolds number. This is to help to locate the error in the input data

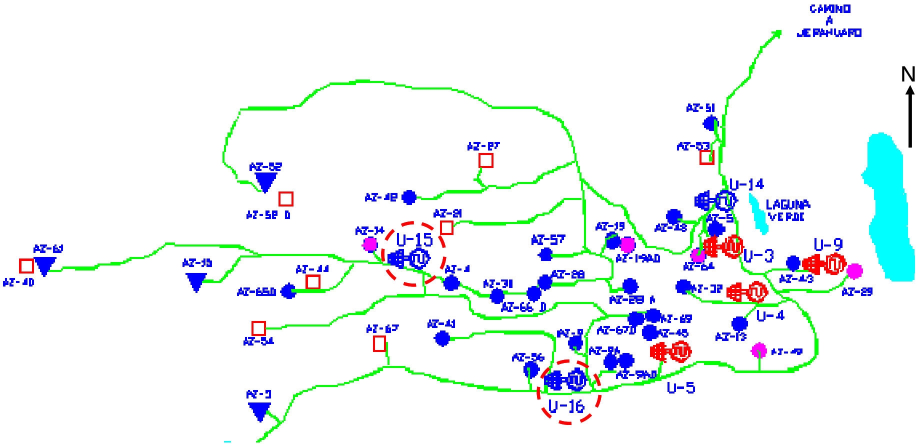

Figure 2: Location map of the northern zone Maritaro in the Los Azufres geothermal field. The plants U-15 and U-16 are marked with dashed circles. The power plant U-15 is fed by the production wells AZ-04, AZ-40, AZ-65D, AZ-69D; whereas AZ-28A, AZ-45, AZ-56, AZ-67 and wells are connected to plant U-16.

Table 1. Steam Flow Balance for Plants U-15 and U-16 and Their Respective Connected Production Wells at the Northern Zone of Los Azufres Geothermal Field.

Well or Plant	Inner diameter of pipeline (m)	Aperture of orifice plate (m)	Pressure at the upstream tapping (Pa)	Pressure diff. (m of Hg-water column)	Steam flow rate (ton/hr)
Plant U-15 and connected production wells					
AZ-04	0.387	0.270	983855	0.056	37.8
AZ-28	0.387	0.1780	997644	0.218	32.5
AZ-40	0.387	0.270	1018328	0.041	32.8
AZ-65D	0.387	0.270	1011434	0.076	44.7
AZ-69D	0.387	0.270	9907494	0.058	38.8
Total of Wells					186.7
U-15	0.737	0.494	956276	0.142	194.0
Plant U-16 and connected production wells					
AZ-28A	0.387	0.127	1094171	0.544	23.4
AZ-45	0.387	0.270	1018328	0.013	18.4
AZ-56	0.387	0.270	976960	0.107	52.0
AZ-67	0.387	0.270	1011434	0.023	24.6
AZ-69D	0.387	0.270	1011434	0.135	59.3
Total of Wells					177.7
U-16	0.737	0.494	956276	0.114	174.1

4. STEAM BALANCE IN LOS AZUFRES GEOTHERMAL SYSTEM

The Los Azufres geothermal system presently has 14 power plants with a total installed capacity of 188 MWe (Garcia et al., 2009). The field is divided in two parts: Tejamaniles in the southern zone (93 MWe) and Maritaro in the northern zone (95 MWe).

The locations of production wells and power plants in the northern Maritaro zone of the Los Azufres geothermal field are shown in Figure 2. In this work, the measurement of steam flow in the plants U-15 and U-16 and the production wells connected to them were performed. The power plant U-15 is fed by the production wells AZ-04, AZ-40, AZ-65D, AZ-69D; whereas AZ-28A, AZ-45, AZ-56, AZ-67 and wells are connected to plant U-16.

Table 1 presents the measured data and calculated values of steam flow for each production well and power plant. In the case of plant U-15, the total steam production from the connected wells is 186.7 ton/hr; whereas the received steam at the plant is 194.0 ton/hr. There is an error of 3.9%. Similarly, there is an error of -2.0% in case of plant U-16. Thus the overall analytical error for the steam flow balance is within ±4%. For practical purposes, the results are considered to be in good agreement.

The possible reasons for the analytical uncertainty of the steam flow measurement in a geothermal system are as follows. The geothermal fluid is separated into vapor and liquid components at the wellhead. Thus, the conditions of temperature and pressure of steam at the well separator are along the saturation curve, and the measurement of pressure or temperature is sufficient at the orifice meter of a well. However, there is a need to measure temperature and pressure at the electricity generation power plant, because there is generally pressure fluctuation at the wellhead. This may be associated with some reservoir processes and/or the existence of gaseous species in the vapor phase. Similarly, the measurement of pressure difference across the orifice plate is crucial. For example, an error of 0.002 m Hg-water column across the orifice plate of power plant U-15 or U-16 is equivalent to 1 ton/hr. Work is still being done to improve the accuracy of measurements.

CONCLUSIONS

The ActiveX component *OrificeMeter* works well for steam flow calculation in a pipeline of a geothermal system. The use of *OrificeMeter* in MS-Excel is helpful in performing a wide range of fluid flow calculations in a pipeline network. The analytical uncertainty for the steam flow measurement in the Los Azufres geothermal field was within ±4%. To improve the analytical accuracy, it is crucial to precisely measure the pressure difference across the orifice plate.

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