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SUBJECT: Temperature Effects on the Measurement of Aqueous Liquid
Level By the Differential Pressure Method and Recommendations
For Placement of Taps on the HRT Replacement Heat Exchanger

TO: Distribution

FROM: R. L. Moore

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TEMPERATURE EFFECTS ON THE MEASUREMENT OF AQUEOUS LIQUID LEVEL
BY THE DIFFERENTIAL PRESSURE METHOD AND RECOMMENDATIONS FOR
PLACEMENT OF TAPS ON THE HRT REPLACEMENT HEAT EXCHANGER

I. SUMMARY

Increasing temperature in an aqueous liquid system results in a decrease in liquid density and an increase in vapor density. When level is measured by the differential pressure method, temperature increase results in a decrease in the effective span of the instrument and a shift in zero. When the instrument reference leg is uncompensated, both zero and span shifts occur with the effects being most pronounced at the higher levels. When the reference leg is compensated, zero shifts are eliminated (instrument zero is at 100% level for this type installation). For control purposes at levels above 50% of full level, the compensated reference leg installation will give the best results. For measurement of levels below 50%, the uncompensated installation is best. As errors in level indications will be produced, in either type installation, by temperature, pressure and steam withdrawal (power) effects, the placement of taps should be such as to place the normal or control level in the region of 50% indicated level.

With respect to the placement of taps on the replacement heat exchanger, it is recommended that three taps be installed as follows:

Upper tap - 16" above centerline

Middle tap - 4" below centerline

Lower tap - vertical from bottom as per B&W Dwg. #48049E-0

It is further recommended that two level instruments be installed. One instrument should be connected between the upper and middle taps and would be used for control. The other instrument should be connected between the upper and lower taps and would be used for indication of levels below the control range. The reference leg of the controlling instrument should be compensated as shown in Fig. 4. The reference leg of the indicating instrument should be uncompensated.

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II. INTRODUCTION

In determining the placement of taps for level measurement on the HRT type heat exchanger, consideration must be given to the various factors influencing the instrument reading and to requirements placed upon the level instrument. As the type of level detection used involves the measurement of liquid head, above the lower tap, by means of a differential pressure measurement, the instrument reading will be dependent on the liquid density and the vapor density. As the liquid density decreases and vapor density increases with temperature increase, the effective range (or span) of the instrument decreases and the zero shifts so as to result in an instrument reading lower than the actual level and, for the case of a controlling instrument, will result in the actual control level being higher than the set point. As will be shown later, the magnitude and direction of the zero shift is dependent on the type of reference leg piping used. In addition to the temperature effects, the level reading and control will be power sensitive since steam withdrawal will result in a decrease in the apparent density of the liquid, due to formation of voids in the liquid, and in an increase in the apparent density of the steam due to entrained liquids. In general, the magnitude of the power effect will be dependent on the residence time of steam voids in the liquid and the effect of an increase in power will be similar to the effect of a temperature increase. As the power effect does not lend itself to ready calculation, the following discussion will be confined to temperature effects. It is recommended that test be performed on the heat exchanger to determine the magnitude of these power effects.

II. ANALYSIS

Fig. 1 shows the type of piping connections used for the present HRT level instrument. In this type installation a long horizontal run is used between the heat exchanger and the vertical legs and the temperature of the vertical legs is maintained relatively constant at a low temperature. Density changes in the vertical legs are therefore small and, if the instrument is calibrated with the system cold, the instrument reading at temperature will be given by the equation

$$R = \left[\frac{X(\rho_l - \rho_v) + \rho_v}{\rho_o} \right] 100 \quad (1)$$

Where X = actual level of water as a fraction of distance between taps

ρ_l = density of liquid

ρ_v = density of vapor

ρ_o = density of liquid in vertical legs.

Equation 1 is plotted in Fig. 2 for various temperatures. If the instrument were calibrated at operating temperature, the instrument reading at other temperatures would be given by the equation

$$R = \left[\frac{(\rho_1 - \rho_v)X + \rho_v - \rho_v'}{\rho_1' - \rho_v'} \right] 100 \quad (2)$$

Where ρ_1 , ρ_v , and X are as defined for equation 1 and

ρ_1' = liquid density at calibration temperature

ρ_v' = vapor density at calibration temperature.

Equation 2 is plotted in Fig. 3 for various temperatures and for a calibration temperature of 500°F.

Fig. 4 shows an alternate type of piping connection wherein density variations of the liquid in the heat exchanger are compensated by maintaining the temperature of a portion of the reference leg at the same temperature as the heat exchanger liquid. Equations for variation of instrument reading with temperature for calibration with system cold and for calibration at operating temperature are given in equations 3 and 4, respectively.

$$R = \left[1 - \frac{(\rho_1 - \rho_v)(1 - X)}{\rho_o} \right] 100 \quad (3)$$

$$R = \left[1 - \frac{(\rho_1 - \rho_v)(1 - X)}{\rho_1' - \rho_v'} \right] 100 \quad (4)$$

where the quantities X , ρ_1 , ρ_v , ρ_1' and ρ_v' are as defined for equations 1 and 2.

Equations 3 and 4 are plotted in figures 5 and 6, respectively.

IV. DISCUSSION OF TAP LOCATIONS

A. Upper Tap Location

As the level will be out of control range if it rises above the upper tap, the upper tap should be sufficiently high to preclude the possibility of immersion during operation but not so high as to unnecessarily extend the instrument range. For the heat exchanger shown on Babcock and Wilcox Dwg. #48049E-0, the upper tap location (16" above centerline) appears to be satisfactory. This location is above the highest desired control level and is above the level to which the water would rise (due to expansion with rise of heat exchanger temperature) when power withdrawal rate is reduced to zero following operation at 5 MW.

B. Lower Tap Location

(1) Case I

If the level instrument is connected to the upper and lower tap shown on B&W Dwg. 48049E-0, the normal water level (8-1/4" above centerline) will be at 84% of indicated full level. If the instrument piping is connected as per Fig. 1 (with cold reference leg), and the instrument is calibrated cold, the zero will shift upscale and the reading for full level will shift downscale as temperature increases and only 70% of the indicated span will be usable at the maximum operating temperature at 536°F (280°C). (See Fig. 2). If the level is to be maintained at a fixed point, the control set point must be lowered, manually, as temperature increases. If the set point were left at 84% and the temperature raised, the actual level would increase with temperature and would be out of control range when it exceeded 100% indicated level (at about 425°F). A further increase temperature would result in a downscale shift in the indicated level with the result that the feedwater valve would open and the level would rise into the steam drum. Protective interlocks would not function to prevent this action as the indicated level would be below the set point. However, if the set point is adjusted to 68%, the level will be controlled at the normal water level (84%) and will rise to 90% at 536°F. This rise corresponds to a 2" rise in level and is well below the dry box.

(2) Case II

If the instrument piping is connected as for Case I above, but the instrument is calibrated at 500°F, the general effects of temperature will be the same as for Case I, but better utilization will be made of the indicated

instrument span at operating temperatures. Variations of controlled level over the operating temperature range from 471°F to 536°F for fixed set point setting appears satisfactory. For a fixed setting of 85% the level will vary from 84% to 91%. However, the level cannot be controlled at the normal water level at low temperature as the indicated level will be offscale (above 100%).

(3) Case III

If the level taps are connected as for Case I and the instrument calibrated cold but the reference leg is compensated as shown in Fig. 4, the full level indication will be independent of temperature but the zero will shift upscale with temperature increase. (See Fig. 5). Temperature effects on the controlled level are small at high levels, being about 2% in the operating range of temperatures from 471°F to 536°F and 8% from 77°F to 536°F for an 84% set point. Low level indications vary drastically with temperature and zero level will indicate 15% level at 400°F (250# sat. Steam).

(4) Case IV

If the instrument piping is connecting as for Case III but instrument is calibrated at 500°C, the general effects of temperature will be the same as for Case III but better utilization will be made of the indicated instrument span at operating temperatures (See Fig. 6). Temperature effects on controlled level are of the same magnitude as for Case III at high level settings. Zero level will read above zero for temperatures above 500°F and below zero for temperatures below 500°F.

(5) Effect of raising lower tap location

If the lower tap is located above the bottom of the tank, the span of measurement will be decreased and the control setting (set point) will be lowered. In general, this will result in a reduction in temperature effects as referred to actual level and results in better level control.

A practical limit is placed on the minimum spacing between the taps by the D/P cell. D/P cell spans of less than 20" H₂O at 25°C and 2000 psi are extremely difficult to obtain and require non-standard instrumentation. For the case of the replacement heat exchanger under consideration, a 20" range places the lower tap at 4" below centerline when the upper tap is located as per Section IV-A. Intermediate tap locations between the bottom of the heat exchanger and 4" below centerline do not offer any particular advantage. When the taps are located 16" above and 4" below the centerline, the desired control level will be at 60%. As shown in Fig. 2, 3, 5, and 6, when the control setting is at 60%, the

level will remain within control range over the full range of temperatures encountered for all cases considered. For the case of the uncompensated (cold) reference leg system significantly increases in control accuracy are obtained with the reduced span and lowered control setting. Accuracy (referred to actual level) will remain the same for the compensated (steam-traced) reference leg system, since the increase in indicated error is offset by the reduction in span.

V. CONCLUSION

If it is assumed that the instrument is in perfect adjustment at operating pressure, if power withdrawal effects on apparent density are ignored, and if, in the case of the cold reference leg system, the operator makes appropriate readjustments of the control setting for various temperatures, the system utilizing taps at the top and bottom of the heat exchanger could be used. However, in practice, the D/P cell can be expected to zero shift slightly with pressure and some power effect will exist. Additionally, the 35% setting does not leave sufficient margin between the control setting and the upper end of the control range to allow for possible long time drifts.

In view of the above considerations, it is recommended that the controlling instrument have a 20" range and be connected to taps placed 16" above and 4" below the centerline. It is further recommended that the reference leg for this instrument be compensated as shown in Fig. 4. If it is desired to read levels below the control range, a third tap should be installed in the bottom of the heat exchanger. A separate D/P cell or float switch should then be connected to the upper and bottom tap and the output of this D/P cell transmitted to a remote indicator located in the control room. In order to give more accurate zero level reading over the range of temperatures encountered, the reference leg for this instrument should be uncompensated.

FIGURE 1

TEMPERATURE EFFECTS ON LEVEL READING

REFERENCE LEG NOT STEAM TRACED
 INSTRUMENT CALIBRATED AT 77°F

FIGURE 2

TEMPERATURE EFFECTS ON LEVEL READING

REFERENCE LEG NOT STEAM TRACED
INSTRUMENT CALIBRATED AT 500° F.

FIGURE 3

FIGURE 4

TEMPERATURE EFFECTS ON LEVEL READING

REFERENCE LEG STEAM TRACED
INSTRUMENT CALIBRATED AT 77°F

FIGURE 5

TEMPERATURE EFFECTS ON LEVEL READING

REFERENCE LEG STEAM TRACED
INSTRUMENT CALIBRATED AT 500° F.

FIGURE 6

$$P_1 = h_o \rho_o + h_l \rho_l + h_v \rho_v + P \quad (1)$$

$$P_r = h_o \rho_r' + h_s \rho_r + P \quad (2)$$

Where ρ_o = density of water in piping to lower tap

ρ_l = density of water in heat exchanger

ρ_v = density of vapor above water in heat exchanger

ρ_r' = density of water in reference leg below lower tap

ρ_r = density of water in reference leg above lower tap

P = vapor pressure in heat exchanger

h_o = elevation of lower tap above d/p cell

h_l = liquid height of heat exchanger water above lower tap

h_v = height of vapor space between water and upper tap

h_s = span = distance between taps

P_1 = pressure at d/p cell from lower tap

P_r = pressure at d/p cell from upper tap

$$\Delta P = P_r - P_1 = h_o (\rho_r' - \rho_o) + h_s \rho_r - h_l \rho_l - h_v \rho_v \quad (3)$$

If $\rho_r' = \rho_o$

$$\Delta P = h_s \rho_r - h_l \rho_l - h_v \rho_v \quad (4)$$

When system is at low temperature and temperatures in heat exchanger and legs are equalized,

$$\rho_r = \rho_l; \quad \rho_v \ll \rho_l; \quad h_v \rho_v \ll h_l \rho_l \quad \text{and the differential pressure is}$$

$$\Delta P_l = (h_s - h_l) \rho_l = (h_s - h_l) \rho_o \quad (5)$$

When the level is below lower tap the differential pressure is

$$\Delta P_o = h_s \rho_o \quad (6)$$

When the level is above upper tap, $h_s = h_l$ and the differential pressure is

$$\Delta P_f = \rho_o (h_s - h_s) = 0 \quad (7)$$

If the span of the instrument is set to register 100% change as the level is raised from lower to upper tap with the system cold, the reading of instrument with system hot for a given level (h_l) will be

$$R = 100 - \left[\frac{h_s \rho_r - h_l \rho_l - h_v \rho_v}{h_s \rho_o} \right] 100 \quad (8)$$

If $X = h_l / h_s$ then $h_l = X h_s$ and $h_v = (1-X) h_s$ since $h_l + h_v = h_s$

$$R = 100 - \left[\frac{\rho_r - X \rho_l - (1-X) \rho_v}{\rho_o} \right] 100 \quad (9)$$

$$= 100 - \left[\frac{\rho_r + (\rho_v - \rho_l) X - \rho_v}{\rho_o} \right] 100$$

If the whole reference leg temperature is equal to the measuring leg temperature

$$\begin{aligned}
 R &= 100 - \left[\frac{\rho_o + (\rho_v - \rho_l)X - \rho_v}{\rho_o} \right] 100 \\
 &= \left[\frac{X(\rho_l - \rho_v) + \rho_v}{\rho_o} \right] 100
 \end{aligned} \tag{10}$$

If the portion of the reference leg above the lower tap is maintained at the temperature of the heat exchanger liquid and the portion below the lower tap is maintained at the temperature of the measuring leg

$$\begin{aligned}
 R &= 100 - \left[\frac{\rho_l - X\rho_l - (1 - X)\rho_v}{\rho_o} \right] 100 \\
 &= 100 - \left[\frac{(\rho_l - \rho_v)(1 - X)}{\rho_o} \right] 100 \\
 &= \left[1 - \frac{\rho_l - \rho_v}{\rho_o} + \frac{(\rho_l - \rho_v)X}{\rho_o} \right] 100
 \end{aligned} \tag{11}$$

If instrument is calibrated at some operating temperature, equations 10 and 11 become equations 12 and 13 respectively, where ρ_1' and ρ_v' are liquid and gas densities at temperature at which instrument is calibrated.

$$R = \left[\frac{(\rho_1 - \rho_v)X + \rho_v - \rho_v'}{\rho_1' - \rho_v'} \right] 100 \quad (12)$$

$$R = \left[1 - \frac{(\rho_1 - \rho_v)(1 - X)}{\rho_1' - \rho_v'} \right] 100 \quad (13)$$