Environmental Effect on Temperature Measurement in Natural Gas Network Balance

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Abstract. Accurate temperature measurements are essential for accounting and balancing natural gas in transmission and distribution networks. In fact, in order to convert gas volumes measured at operational conditions into standard reference ones, the accurate knowledge of both the thermodynamic conditions of the gas (i.e. temperature and pressure) and its chemical composition is necessary. In the case of large flow-meters, even small measurement errors (e.g. deriving from difference between the ambient temperature and the temperature of the fluid) can become relevant in terms of “unaccounted for gas”, especially when they do not find adequate compensation during the annual balancing of the network. To this aim it is necessary to carefully evaluate the systematic errors affecting temperature measurement which depend on instrumentation metrological characteristics as well as on thermo-fluid dynamic issues. In some cases, thermal insulation of the flow-meter and both upstream and downstream measuring stretches should be necessary. In this paper the authors present the results of an experimental study on the installation effects of temperature probes in closed conduits, performed at different operating conditions of natural gas transmission networks and aimed at estimating the typical random and systematic effects, and proposing optimal installation and operative solutions.

1. Introduction

One of the most important applications of fluid temperature measurement in a closed conduit is that in natural gas transport and distribution networks, due to its relevance both in the accounting of gas consumption and in the balancing of networks [1-3]. In fact, in order to convert gas volumes measured at the operational conditions into the reference ones, it is necessary to know both the thermodynamic conditions of the gas (i.e. temperature and pressure) and its chemical composition. This correction function is performed by volume conversion devices which can be integrated into the meter (in the case of domestic meters) or separated [4]. In the case of large flow rates, even small measurement errors can lead to significant errors on the quantities of gas volumes accounted for. This happens especially when such errors are not adequately compensated during the annual balancing. In this case, it is necessary to carefully evaluate the systematic errors in temperature measurements and, in several cases, to thermally insulate the meter and the entire measurement stretch (upstream and downstream).

For fiscal purposes in natural gas networks, platinum (e.g. Pt100) resistance temperature sensors (RTDs) are generally used, typically protected by a relatively thin (about 5-6 mm) stainless steel sheath [4-5]. The sensor is generally placed in a thermowell both to protect the sensor from operational conditions (e.g. corrosion, abrasion, impact, bending, compression), and to allow easy replacement and
calibration (i.e. to allow the instrument to be removed during exercise without stopping the flow). Thermowells must be chosen and designed considering some parameters such as pressure, gas flow rate, presence of vibrations and corrosive agents.

However, the use of thermowells makes the measurement even more complex as there is no direct contact between the temperature sensor and the gas stream, affecting both the response time and the accuracy of the measurement itself. In fact, in the design stage of thermowells the mechanical requirements are generally in contrast with the metrological ones. As for example, the bending strength requirements and the resonance issues (i.e. the natural frequency should be sufficiently greater than the frequency induced by the vortices that are generated on the well itself) would require thermowells to be short and thick [6], but these latter determine an increase in static (short wells) and dynamic (thick wells) errors. From a metrological point of view, therefore, the use of thermowells should be avoided as the bare sensor always shows a better response time and "fin effect". The choice of the sensor-thermowell coupling, the position and connection of the thermowell and, finally, its length and shape are extremely important issues for the accuracy of the gas temperature measurement.

As regards the sensor-thermowell coupling, it is essential to ensure a good thermal contact. In particular, the tip of the sensor should be in contact with the edge of the thermowell. Some installation schemes include spring-loaded sensors which help ensure the best contact in any installation condition and orientation (e.g. vertical mounting from below). The sensor-thermowell radial clearance should also be as limited as possible since the air itself acts as a thermal insulator. The use of conductive pastes or oils can partially mitigate this problem.

The thermowell positioning can play an essential role especially in the case of small-sized pipes. An angled insertion can increase the immersion length compared to a perpendicular one. If the insertion lengths are too short (unless the tip extends beyond the axis of the pipeline) it would theoretically be applied inserted in the bend.

The most common connecting options for thermowells are represented by: 1) threaded (which, although allowing easier installation and removal, show limits in maximum pressure and emissive losses); 2) welded (mainly used in applications with high velocity, temperature and pressure flow); 3) flanged (mainly used in corrosive environments and high speed, temperature and pressure).

Thermal and mechanical performance of thermowell also varies according to the shape of the stem: a tapered or stepped stem, although slightly more expensive, provides a faster response, generates lower pressure drops and it is less sensitive to conduction error and vibrations. Different stem shapes are available on the market: tapered, straight or stepped. Figure 1 shows a sketch of the typical installation conditions of thermowells and of the different related connections.

![Figure 1 – Installation options for thermowells: (a) coupling sensor-thermowell [7]; (b) thermowell connection to the pipe [8]; (c) thermowell position [9]](image)

The amplitude of temperature measurement errors depends not only on strictly instrumental issues but also on specific thermo-fluid dynamics aspects of the installation [10-11] such as: a) the difference between the gas temperature and the external one (variation of the average temperature between
upstream and downstream of the meter; b) the immersion length and the diameter of the stem; c) the difference between the mean radiant temperature of the pipeline and the gas temperature; d) the relationship between the radiative and convective conductance (in which the gas velocities and the emissivity of the probe/thermowell play an essential role) e) any distortion of the temperature profile inside the pipe (i.e. stratification of temperatures from top to bottom); f) the isobaric thermal expansion coefficient of the gas. In the case of non-stationary conditions, the thermal capacity of the thermowell itself also has a considerable influence.

As known, the vibrations of the thermowell induced by the gas flow can represent a problem for pipes with a diameter greater than 300 mm; in this case conical rather than cylindrical thermowells are used. Furthermore, to improve measurement accuracy it is essential to optimize the immersion depth of the probe inside the pipe. In this regard, the ISO 15970 [12] and UNI 9167 [13] standard suggests an immersion depth equal to at least 1/3 of the internal diameter of the pipeline (for DN>300 mm a minimum length of 100 mm is requested). Furthermore, in the case of small pipes (e.g. DN<100 mm) or when the immersion depth exceeds 3/4 of the diameter of the pipeline, installation with an inclination of 45 ° with respect to the flow direction or in a bend is allowed (Figure 1c).

The latter situation is not recommended due to the number of straight lengths upstream and downstream of the flow meter to be guaranteed. The greater distance of the thermowell from the flow meter can in fact lead to a further systematic error due to the progressive heating/cooling of the fluid, especially when the gas temperature changes considerably due to thermal gradients with the external environment. Finally, aimed at reducing the radiative exchange between the pipe and the sensor, it is necessary to minimize the surface emissivity of the thermowell. Typically, thermowells used in natural gas transmission pipelines are made of polished stainless steel. Despite this precaution, since it is not possible to know the real wear of thermowells in operation, it is not possible to neglect the radiative contribution of the pipe when the temperature difference between the pipe surface and the sensor becomes relevant.

Recent studies on the influence of installation conditions on the accuracy of the temperature measurement in transmission and distribution natural gas networks investigated flanged thermowells through a CFD analysis of the temperature range as the flow conditions vary [10] and through an experimental analysis on 3, 8 and 24 " pipes with estimated errors lower than ± 0.5 °C at a gas velocity of 1 m/s at high pressure condition [14]. On the other hand, no systematic experimental studies have been carried out to evaluate all the installation effects that can influence the measurement.

In this study the authors present and discuss the results of an experimental test campaign designed to estimate temperature measurement errors of a fluid stream carried out by means of a thermowell in a pipe at ambient pressure and due to the conductive and radiative exchanges between the thermowell and the pipe.

2. Theory and Methods
To allow accurate accounting of natural gas consumption and the balancing of transmission and distribution network, it is necessary to refer natural gas measured at operational conditions to the reference thermodynamic ones (i.e. 288.15 K and 1.01325 bar). In transmission network measurement systems, therefore, a volume correction device is associated with the flow-meter usually consisting of a flow computer (electronic device for data acquisition and processing) and pressure and temperature transmitters. The volume at reference conditions for volumetric flow-meter is then given by:

\[ V_S = V \cdot KTvo = V \cdot \frac{P}{P_S} \cdot \frac{T_S}{T} \cdot \frac{Z_S}{Z} \]  

(1)

where: i) \( KTvo \) is the correction dimensionless coefficient; ii) \( V \) and \( V_S \) are the gas volumes at operational conditions and reference ones; iii) \( P \) and \( P_S \) are the absolute pressure at operational conditions and reference ones; iv) \( T \) and \( T_S \) are the absolute temperatures at operational conditions and reference ones; v) \( Z \) and \( Z_S \) are the dimensionless compressibility factor at operational conditions and reference ones. For the venturimetric measuring lines the dimensionless correction \( KTve = \sqrt{KTvo} \).
By applying the error and uncertainty propagation law [15] to equation (1), it can be pointed out that the weight (i.e. $w = +1$) of the relative error of the gas volume at operational conditions $V$ is in absolute value equal to the one of the relative error of the temperature measurement used for calculation of the volume at reference conditions $V_s$ (i.e. $w = -1$):

$$\frac{E_{V_s}}{V_s} = \frac{\Delta E_V}{V} + \frac{E_{VT}}{KTvo} = \frac{E_V}{V} + \frac{E_P}{P} - \frac{E_T}{T} - \frac{E_Z}{Z}$$

where $E$ is the absolute error of the different parameters $V, P, T$ e $Z$.

2.1 Analysis of systematic temperature errors (simplified model)

The temperature measurement errors related to the conductive and radiative heat exchange on the thermowell come from the temperature difference between the natural gas and the pipe. For this reason, the measurement section and the sensors are subject to heating/cooling due to external environmental conditions, where even the solar radiative exchange contributes significantly in respect to the convective heat flows with the external air. In fact, in transmission networks, the gas coming from the underground pipelines is measured after passing a section of pipes exposed to the external environment (e.g. to allow transit in the regulation and measurement systems, odorization, access to the PIGs, etc.). This can cause significant changes in the measured temperature which is influenced by factors such as: i) the presence of preheating systems to cope with the Joule-Thomson effect (i.e. lowering of the temperature following a gas pressure reduction); ii) the absence of a protected environment (e.g. a regulation and measurement cabin) or of insulation of the measurement sections able to protect the measurement system from the external environment. For this reason, the measurement stretch and the measuring devices are subject to heating/cooling due to external weather conditions, especially when the measurement plant is located outdoor.

From the theoretical point of view, measurement errors can be roughly estimated analytically on the basis of simple equations by evaluating: a) the conductive heat flow between the free edge of the sensor and the edge of the thermowell mounted on the pipe wall with respect to the convective heat flow between the thermowell and the gas stream; b) the radiative heat flow between the thermowell and the pipe; c) the longitudinal temperature gradients (i.e. between the section where the thermowell is located and that of the primary element) and vertical (i.e. in the temperature measurement section). In the following, for a simpler understanding of the phenomenon, all temperature errors have been referred to the $T_w - T_g$ thermal gradient which determines the error itself.

2.1.1 Systematic error due to conductive heat exchanges along the thermowell.

A simplified model for evaluating the measurement systematic error associated with sensor immersion length can be obtained by assuming the thermowell as a “thin” cylindrical stem outgoing the wall of the pipe. In the event that the gas is at a different temperature than that of the sensor, a thermal power is transmitted by conduction through the length of the thermowell to the wall of the pipe. Furthermore, on the lateral surface of the thermowell also a surface heat exchange due to the combined action of convection and radiation is observed. The balance equation at stationary conditions for the elementary segment of length $\delta x$, under the simplifying hypotheses of: i) homogeneous and isotropic material of the thermowell; ii) absence of radial temperature gradients in the stem $T = T(x)$; iii) heat transfer coefficient constant and uniform over the entire exchange surface, iv) absence of radiation, is given by:

$$-kA \frac{dT}{dx} = -kA \frac{dT}{dx} + \frac{d}{dx} \left( -kA \frac{dT}{dx} \right) \delta x + \bar{h}P \delta x (T - T_g)$$

where $k$ is the average thermal conductivity of the thermowell and of the sensor stem; $h$ is the convective heat transfer coefficient; $A$ is the perpendicular surface area of the thermowell; $P$ is the perimeter of the thermowell; $T$ and $T_g$ the thermowell and gas temperatures in the generic section $x$, respectively. Under
the hypothesis of negligible heat exchange in the top of the stem, from relation (3) it is possible to
determine the insertion systematic error $e_{T,k}$ due to conduction along the thermowell:

$$e_{T,k} = \frac{T - T_g}{T_w - T_g} = \frac{1}{\cosh(mL)}$$  (4)

where $m = \sqrt{\frac{(hP)}{(kA)}}$, $T$ is the thermowell temperature at section $x = L$, $T_w$ is the temperature la of
the pipe wall, $L$ is the thermowell immersion length. From equation (4) it can be pointed out that error
$e_{T,k}$ due to conductive effect decreases as the thermowell length and flow velocity increase, whereas it
increases when the radius and thermal conductivity of the thermowell increase (see fig.2a). As for example,
in the case of a thermowell of 0.08 m length whose thermal conductivity ranges between 20
and 60 Wm$^{-1}$K$^{-1}$, the error $e_{T,k}$ ranges between 40 and 70%.

2.1.2. Systematic error due to the radiative heat exchange between the thermowell and the pipe.
The radiative heat exchange between the thermowell and the internal walls of the pipe can significantly
influence the measured value of the gas temperature. Given the high ratio between the cavity area in
which the thermowell is located and the measuring area and also considering the surface state and the
degree of oxidation of the pipeline internal walls metal surfaces, the pipe walls emissivity can be
neglected, but not that of the sensor. Furthermore, given the temperatures of the pipeline walls and the
well, it can be pointed out that radiative exchange affects only the infrared range. As a consequence, the
author considered the average emissivity well at room temperature. Therefore, under the hypothesis of
steady state, transparent natural gas (this condition is true since the transversal dimensions of pipes is
typically lower than 1 m) and negligible conductive thermal power through the length of the thermowell
(whose effects has been considered separately in paragraph 2.1.1.), the thermal balance can be written
as follows:

$$\sigma \varepsilon (T_w^4 - T^4) = \bar{h}_c(T - T_g)$$  (5)

where $\sigma$ is the Stefan-Boltzmann constant; $\varepsilon$ is the emissivity of the thermowell surface; $T_w$ and $T$
the absolute temperature of the cavity and that of the thermowell, respectively. The systematic error $e_{T,r}$
due to the radiative heat exchange is then given by:

$$e_{T,r} = \frac{T - T_g}{T_w - T_g} = \frac{1}{\bar{h}_c} \sigma \varepsilon (T_w^4 - T^4)$$  (6)

From equation (6) it can be pointed out that the measurement error due to the radiative effect mainly
depends on the convective heat exchange coefficient, $\bar{h}_c$, on the sensor emissivity $\varepsilon$, on the fourth power
of the temperature of the sensor $T$ and the temperature of the cavity $T_w$. The increase of $\bar{h}_c$ and the use
of low emissivity thermowells would allow to reduce the measurement error. As for example, Figure 2b
shows the trend of the error due to the radiative heat exchanges between the thermowell and the pipe,
as a function of the convective exchange coefficient and of the thermowell emissivity. The graph shows
that the systematic error due to irradiation is lower than the insertion one (less than 30%) and it is equal
to about 15% at atmospheric pressure and at 0.5 m s$^{-1}$ gas velocity, whereas it is lower than 3% at 30
bar (e.g. about 0.6 °C with $\Delta T$ = 20 °C between gas stream and pipe).

2.1.3 Systematic error due to the longitudinal and vertical thermal gradients of the gas.
A further measurement error is due to the longitudinal thermal gradient represented by the temperature
difference between the section in which the flow-meter is located and that of the thermowell. In fact, in
the passage through the pipe, the radiative and convective heat exchanges between the gas stream and
the pipe cause a variation in the gas temperature. Thus, the longitudinal distance between the thermowell
and the flow-meter can lead to significant differences between the temperature measured in the
thermowell and that of the gas stream in the case of non-negligible heat exchanges between the gas itself
and the external environment. Under the hypothesis of ideal gas and limited thermal exchange gradients,
the measurement error $e_{T,c}$ due to the temperature difference between the section in which the flow-meter is located and that of the thermowell can be obtained as follows:

$$e_{T,c} = \frac{T - T_g}{T_w - T_g} = \frac{1}{A} \frac{h_c \left( T_w - \frac{T + T_g}{2} \right)}{\rho V c_p}$$

(7)

where $V$ is the volumetric flow-rate at operational conditions; $A$ is the internal surface of the pipe between the flow-meter and thermowell sections; $c_p$ is the specific heat capacity of the gas; $\rho$ is the gas density; $T - T_g$ is the temperature variation between the flow-meter and thermowell sections. From equation (7) it can be pointed out that error $e_{T,c}$ increases when convective heat exchanges increase whereas it decreases when gas flow-rate increases (see Figure 2c). Furthermore, the asymmetry of radiative heat exchanges (typical of summer regimes) can lead to relevant temperature differences between the upper and lower sections of the pipe. Such asymmetry causes a systematic error of the same sign of the above described ones, when the thermowell is mounted in vertical position in the upper section (i.e. the one exposed to direct solar radiation), but it can be generally neglected in respect to others contributions.

![Figure 2](image-url)

Figure 2 – Systematic Error due to heat exchanges: a) conductive along thermowell; b) radiative between thermowell and cavity (pipe); c) convective and radiative between gas stream and pipe.

2.2. Experimental measurement campaign

To experimentally estimate the temperature measurement error in a gas transmission pipe and to quantify the effect on the calculation of volumes, the authors designed and carried out an experimental measurement campaign at the LAMI laboratory of the University of Cassino and Southern Lazio, LAT 105 accredited by ACCREDIA. Before the experimental campaign, all the temperature sensors have been calibrated by comparison with the laboratory reference standard (Pt25) in a thermostatic bath at different test temperatures. Measurements have been carried out on a DN160 gas pipe with a low emissivity thermowell of 80 mm length and diameter of 15 mm immersed in a temperature controlled water bath aimed at keeping the surface temperature of the pipe constant. Figure 3 shows the experimental layout for the laboratory measurements.
The flow in the pipe has been obtained by drawing in an air flow at different velocities. The pipe section has been equipped with three Pt100 immersion resistance thermometers (respectively for measuring the internal temperature of the thermowell, of the pipe inlet and outlet sections) and two Pt100 contact resistance thermometers (respectively for the external and internal surface temperature of the pipe). An additional shielded Pt100 resistance thermometer was installed directly in the air flow close to the edge of the thermowell.

3. Results
In order to replicate the different ambient and flow conditions in the natural gas measurement and regulation plants, surface pipe temperature conditions of 8 and 12 °C (i.e. winter regime) and 30, 40 and 50 °C (i.e. summer regime) have been reproduced. For each temperature, different air flow velocities have been set within the pipe. The results obtained are reported in Table 1 for the winter regime and Table 2 for the summer one.

Table 1 – Experimental results (winter regime)

| $T_{\text{set}}$ °C | $w_g$ m s$^{-1}$ | $T_{\text{well}}$ °C | $T_g$ °C | $T_{\text{pipe,ext}}$ °C | $T_{\text{pipe,int}}$ °C | $T_{g,\text{in}}$ °C | $T_{g,\text{out}}$ °C | $E_T$ °C | $E_T$ % |
|-------------------|-----------------|-----------------|-------|-----------------|-----------------|-----------------|-----------------|--------|--------|
| 8                 | 0.50            | 15.85           | 20.06 | 8.32            | 10.10           | 20.87           | 17.84           | -4.21  | 42%    |
|                   | 3.00            | 17.73           | 20.26 | 8.72            | 13.18           | 20.62           | 18.63           | -2.53  | 36%    |
|                   | 7.00            | 19.45           | 20.94 | 11.09           | 16.10           | 21.11           | 19.75           | -1.49  | 31%    |
| 12                | 0.50            | 17.52           | 20.14 | 12.53           | 13.62           | 20.93           | 18.74           | -2.62  | 40%    |
|                   | 3.00            | 19.08           | 20.26 | 13.93           | 16.18           | 20.56           | 19.41           | -1.18  | 29%    |
|                   | 7.00            | 20.01           | 20.71 | 14.54           | 17.65           | 20.88           | 19.94           | -0.70  | 23%    |

Table 2 – Experimental results (summer regime)

| $T_{\text{set}}$ °C | $w_g$ m s$^{-1}$ | $T_{\text{well}}$ °C | $T_g$ °C | $T_{\text{pipe,ext}}$ °C | $T_{\text{pipe,int}}$ °C | $T_{g,\text{in}}$ °C | $T_{g,\text{out}}$ °C | $E_T$ °C | $E_T$ % |
|-------------------|-----------------|-----------------|-------|-----------------|-----------------|-----------------|-----------------|--------|--------|
| 30                | 0.50            | 27.56           | 24.26 | 30.47           | 29.34           | 23.02           | 26.00           | 3.30   | 65%    |
|                   | 2.94            | 23.87           | 21.73 | 30.18           | 26.13           | 21.53           | 23.28           | 2.14   | 49%    |
|                   | 6.87            | 24.77           | 22.89 | 30.27           | 27.04           | 22.84           | 24.14           | 1.88   | 45%    |
| 40                | 0.50            | 33.48           | 25.80 | 40.71           | 38.49           | 22.51           | 30.08           | 7.68   | 61%    |
|                   | 2.94            | 26.78           | 22.72 | 40.03           | 32.16           | 22.31           | 25.64           | 4.06   | 43%    |
|                   | 6.87            | 30.57           | 24.17 | 49.59           | 39.17           | 23.81           | 28.25           | 6.40   | 43%    |
| 50                | 0.50            | 39.80           | 28.20 | 50.74           | 47.34           | 22.97           | 34.67           | 11.60  | 61%    |
|                   | 2.94            | 29.91           | 22.96 | 49.93           | 38.85           | 22.05           | 27.41           | 6.95   | 44%    |
|                   | 6.87            | 30.49           | 24.05 | 49.58           | 39.13           | 23.68           | 28.16           | 6.44   | 43%    |
4. Discussion and Conclusions

The installation effects of the sensors, as well as the absence of thermal insulation of the measurement stretch, lead to systematic errors in the measurement of the gas stream temperature in transmission networks, in particular due to: i) the conduction on the stem of the thermowell; ii) the irradiation of the duct on the stem, iii) heating/cooling of the fluid downstream of the flow-meter (i.e. in the typical position of the thermowell). The results of the experimental analysis at ambient pressure show the systematic overestimation (underestimation) of the temperature measured in summer (winter) regime with errors ranging between +1.9 °C and 11.6 °C (corresponding to about 43% and 65% of the $T_w - T_g$ thermal gradient) in summer condition and between -0.7 °C and -4.2 °C (corresponding to about 23% and 42% of the $T_w - T_g$ thermal gradient) in winter condition as the velocity increase between 0.5 to 7.0 m/s. The magnitude of this effect should not be surprising since the authors reproduced in the laboratory extreme operational conditions and confirm the theoretical model reported in fig.2a e 2b. On the other hand measurement errors significantly reduce as: i) the immersion length of thermowell increases (e.g. $L > 0.20$ mm, see fig.2a); ii) the pressure and gas velocity increases (see fig.2b); iii) the distance between thermowell and flow meter decreases (see fig 2c).

From the analysis carried out it emerges that aiming at reducing temperature measurement errors in transmission networks and, consequently, at reducing the unaccounted for gas in the network balancing, it would be appropriate to ensure: i) the thermal insulation of the measurement lines and/or the shielding of the temperature sensors; ii) the adequate sizing (length and thickness) and installation (e.g. oblique for small diameters) of the thermowells; iii) the use of suitable conductive coupling fluids in the thermowell-probe coupling; iv) the use of low-emissivity or shielded thermowells; v) the thermowell positioning not too far from the flow-meter (i.e. at maximum two diameters lengths).

In order to accurately estimate the influence of these issues in the gas transmission networks, it is also considered useful: a) to carry out further experimental campaigns varying the thermowell dimensions and pipes as well as the operating and environmental conditions (e.g. high pressure, solar radiation) both in the laboratory and in the field; b) to extend the theoretical analysis of heat exchange to a more in-depth numerical sensitivity analysis in order to allow a more accurate evaluation of the systematic effects on gas stream temperature measurements in the typical operational conditions of gas transmission networks.

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