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# Simultaneous determination of gas leakage location and leakage rate based on local temperature gradient

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ABSTRACT

In this study, a quantitative non-contact detection method for gas leakage problem based on infrared thermography technology is developed. First, the relationship between the gas leakage rate and the temperature gradient at the edge of the leaking hole is established based on thermodynamics, dimensional analysis and numerical methods. Second, the temperature fields surrounding the gas leakage location are extracted using an infrared thermal imager. Both the gas leakage location and leakage rate are obtained for the damaged rubber seals. Finally, the detections of gas leakage location with arbitrary shape and no obvious temperature difference are discussed and generalized. These results will play an important role in detecting the leakage rate for the damaged seal structures or containers.



## 1. Introduction

Nowadays the demand for gas tightness is more stringent for the rubber-sealed structures [1], such as pipes and vessels. During the service process of the seal structures, the damage of the seal materials will gradually evolve into tiny holes under alternating pressure and temperature [2], reducing the reliability and safety of the structures. In fact, the damaged rubber seal because of the formation of tiny holes can lead to catastrophic consequences, such as flight accidents caused by gas leakage. For other cases, fire or even explosions disasters occur because of gas leakage in the high temperature gas or natural gas pipelines [3]. The larger the leak rate, the more serious the leak and the more serious the consequences of the accident. If the leakage rate can be accurately measured, the extent of the leakage will be judged and the corresponding effective response will be taken accordingly. Therefore, it is a challenging task to detect the gas leakage rate and location at an early stage in many sealed structures and equipment.

Existing gas leakage detection methods mainly consist of the bubble method, helium detection method [4], acoustic method [5,6], differential pressure detection method [7,8], laser detection method [9] and infrared thermography method [10]. Usually, the gas within the sealed structure expands when it leaks out from a high-pressure to a low-pressure environment, and then ultrasonic waves will be produced. Both the leaking location with the positioning accuracy of about 2 mm and the leaking rate with sensitivity of 0.33 L/s are obtained through sensing and post-processing of ultrasonic signals [11–14]. However, the ultrasonic waves produced by the gas expansion require higher-pressure gradients, which cannot determine the size of the leakage hole. Ke et al. [15] adopted the differential pressure detection method to investigate the gas leakage along the contact interface between the rubber seal and the metal by means of the designed detection system with a high measure precision of 0.6 mL/min. Meanwhile, the infrared radiation intensity can be observed and sensed by the laser-imaging viewfinder. For some gases (e.g., $CH_4$ and $SF_6$) with a very strong absorption of long-wavelength infrared radiation, the gas leakage on the device surface is obtained using the laser detection method [16]. For instance, Ikuta et al. [17] proposed differential absorption lidar system to monitor $CH_4$ leakage of 100 ppm with a resolution of 15 m and a detection range up to 500 m. Sampaolo et al. [18] reported a $SF_6$ leakage laser sensor based on mid-IR quartz-enhanced photoacoustic spectroscopic technique with a sensitivity of leak flows in the $10^{-9}$ mbar·L/s range.

Infrared thermography has emerged as a full-field and non-contact temperature measurement method in recent years, whose principles are described in detail by Meola and Carlomagno [19]. So far, infrared thermography has also been widely used in the non-destructive monitoring [20,21], building diagnostics [22], disease detection [23], materials evaluation [24], automatic industry [25]

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and so on. Meanwhile, some researchers also detected the gas leakage using infrared thermography [26–29]. Some models and algorithms have been proposed to evaluate the applicability and performance of the gas leakage detection method by infrared thermography. For example, Li et al. [30] proposed a minimum resolvable gas concentration (MRGC) model to evaluate the performance of the gas detection system about infrared imaging, and the MRGC value can reach about 1000 ppm·m. Kroll et al. [31] proposed a statistical algorithm based on the temperature characteristics at the leaking position, and the experimental results indicated that a moderate pressure difference (5 bar) and a small leak diameter (0.6 mm) can cause a detectable effect. Besides, the comparison between the infrared thermography method and the other leakage detection techniques has also been investigated. Slobodan et al. [32] studied the quantitative detection method of ultrasound and infrared thermography for compressed air leakage by the graph of the leakage flow with the sound level and detected temperature change. And it has been found that ultrasound method has the limitation by the background noise and infrared thermography offers good detection results for the orifices diameter greater than 1.0 mm. Samuel et al. [33] also presented the robotic system for the remote gas leak detection using infrared thermography, and the challenging tasks like ramp climbing and remote leak detection with a distance of 20 m were successfully finished. The leakage quantification is very important in the field of gas leakage detection. Zeng et al. [34] defined the response factors to characterize relative sensitivity of one compound vs. another compound, avoiding the calibrations for each of these compounds in the quantitative leakage measurement by infrared gas imagers. Kasai et al. [35] detected propane gas leakage using infrared absorption and established the relationship between the gas leakage concentration and the infrared absorption intensity. Nevertheless, the carbon infrared emitter needed to be cooperated with the infrared camera in this system. Therefore, most of research works cannot realize the quantitative measurement of the leakage rate and location by infrared thermography, and some methods can only be used for the leakage detection of the specific gas, which limits the application range of leakage detection method by infrared thermography.

The present work involves a quantitative study of the gas leakage from round holes in the container using infrared thermography and establishes the quantitative relationship between the leakage rate and the temperature gradient. This study also proposes a gas leakage detection method for determining the leakage location and the leakage rate, whose performance is verified through the gas leakage experiments.

## 2. Thermodynamic analysis of the gas leakage

Fig. 1(a) shows the container with a leakage hole. The gas leaking from the container has a higher temperature than the outside environment, and there is a specific temperature distribution near the leakage hole. It is assumed that a circular temperature profile is gradually extended out. Fig. 1(b) shows the temperature field of the container with a hole under the gas leakage condition, indicating the obvious recognition characteristics of the temperature field at the leakage location. The temperature around the leakage hole dramatically changes. Moreover, the temperature gradient near the edge of the hole may have a high correlation with the gas leakage.

A theoretical analysis of the temperature gradient and gas leakage is performed by adopting a simplified axisymmetric model for the gas heat transfer problem in an infinite plate containing a hole. Fig. 2 shows the simplified axisymmetric model of the gas leakage from the hole, where $p_0$ and $T_0$ are the pressure and the room temperature of the air, respectively; $p_1$ and $T_1$ are the pressure and the temperature of the gas in the container, respectively; $r$ is the hole radius; and $t$ is the solid wall thickness.

Dimensional analysis is a useful tool for analyzing many thermodynamics problems. The Buckingham pi-theorem [36] indicates that a physical equation containing K variables is equivalent to the function of K–M dimensionless parameters, where M is the number of independent dimensions. The temperature gradient $\frac{\partial T_{solid}}{\partial n}$ at the edge of the leakage hole is obtained as follows:

$$\frac{\partial T_{\text{solid}}}{\partial n} = f(Q, T_0, C_{pgas}, \lambda_{gas}, T_1, C_{psolid}, \lambda_{solid}, r, t) \quad (1)$$

where $Q$ is the gas mass flow (i.e., gas leakage rate); $C_{Pgas}$ and $C_{Psolid}$ are the specific heat capacities of gas and solid, respectively; $\lambda_{gas}$ and $\lambda_{solid}$ are the heat conductivity coefficients of gas and solid, respectively.

The heat flux $q$ along the edge of the leakage hole is expressed in Eq. (2) based on the heat conduction differential equation and the dimensional analysis:

$$q = \lambda_{solid} \frac{\partial T_{solid}}{\partial n}\bigg|_{wall} = \lambda_{gas} \frac{\partial T_{gas}}{\partial n}\bigg|_{wall} \quad (2)$$

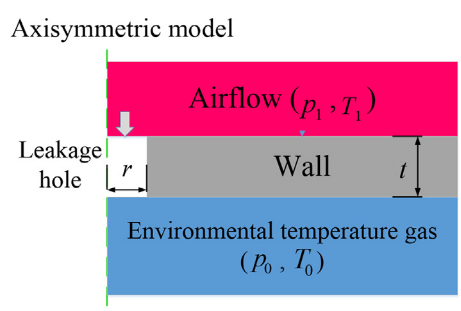


**Fig. 2.** Axisymmetric model of the gas leakage in an infinite plate with a hole.

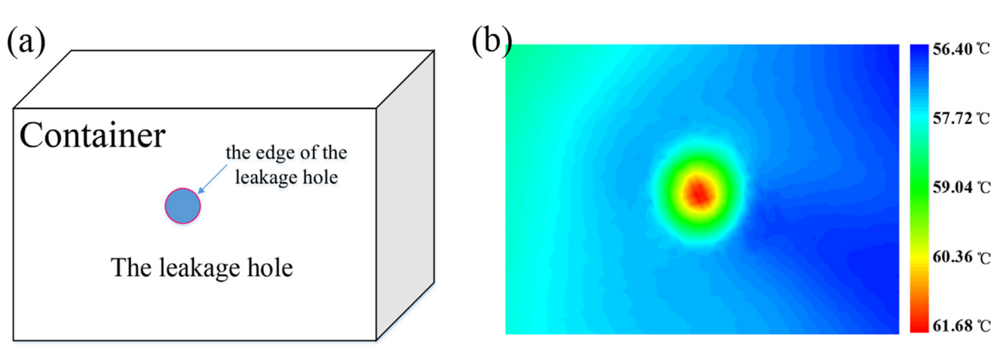


**Fig. 1.** Leakage hole in the container and wall temperature field: (a) Container with the leakage hole. (b) Wall temperature field of the container.