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Research Paper

A study on a real-time leak detection method for pressurized liquid refrigerant pipeline based on pressure and flow rate

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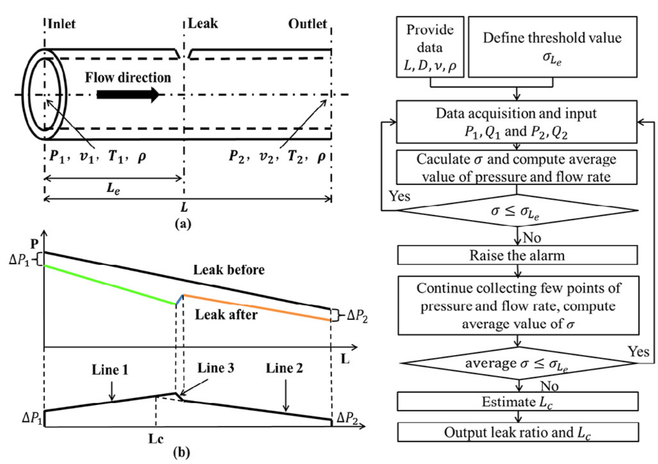
HIGHLIGHTS

- A real-time leak detection method is developed for ammonia pipeline in cold storage.
- A locating algorithm based on pressure difference profile is provided.
- This method is validated by R22 and ammonia leak experiments.
- The minimum detectable leak ratio is 1% for R22 and 4% for ammonia.
- The location estimating errors are –27% ~ 17% for R22 and –27% ~ 27% for ammonia.

GRAPHICAL ABSTRACT



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ABSTRACT

Leakage from pressurized liquid ammonia pipeline has been a serious problem in large commercial cold storages because it might release large amount of liquid ammonia and without safety supervision in daily operations. The present paper shows a detection method for a pressurized liquid ammonia pipeline with a leak. The variations of pressure, flow rate and pressure difference profile are studied. A leak indicator (σ), proposed with the one-dimensional steady-state flow model, is used to detect the leak occurrence by comparing it with a threshold value (σ_{Le}). A locating algorithm based on pressure difference profile along the pipeline is also proposed, which has considered the effect of the static pressure increase at the leak point. Experiments on different leak positions and ratios from liquid R22 and ammonia pipelines are carried out to validate this method. It is found that, with a relatively low false alarm rate (as three percent), the minimum detectable leak ratio reached 1% for the R22 pipeline and 4% for the ammonia pipeline. The locating errors are between –27% ~ 17% for R22 pipeline and –27% ~ 27% for ammonia pipeline.

1. Introduction

Ammonia is widely used in large commercial cold storages as a refrigerant for its attractive properties such as good environmental potential, cost-effectiveness, better performance of heat transfer and larger latent heat of vaporization than most other refrigerants

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[1]. Because of the environmental issues related to the refrigerant and energy consumption, studies of the utilization of ammonia as an alternative refrigerant have recently received increasing attention [2]. The applicable occasions have been extended to supermarket [3] and residential areas [4]. However, the ammonia released to the atmosphere is harmful. The life-threatening exposure time will not exceed 5 minutes when the concentration is slightly higher than 1500 ppm [5]. Moreover, chemical explosions may happen if the ammonia concentration reaches the explosive limits (15%–28%) in a limited space. Therefore, adequate attention is required on safety while ammonia refrigeration techniques are promoted.

The liquid pump loop is commonly used in ammonia refrigeration systems to ensure the adequate liquid supply. The pipeline between the pumps and evaporators is usually hundreds of meters long and contains a large amount of the pressurized liquid ammonia. Because of the complex layout of this pipeline and the thick insulation layer, there is a lack of safety supervision in daily operations. Therefore, it is necessary to take additional precautions for security of the pressurized liquid ammonia pipeline.

There are some researches and studies on the fault detection and diagnosis (FDD) of air handling units [6], chillers [7], heat pumps [8], power plants [9,10] and refrigeration systems [11,12]. Among them, the refrigerant leak detection is one of the interest fault detections. Various techniques of leak detection can be divided into two main categories [13]: hardware based (acoustic [10], gas sensing [14–16], etc.) and software based (statistical [6–9], reference model [6,11,12], etc.). However, there are barely any further studies focused on the FDD of liquid ammonia pipeline in cold storages. The most widely used methods at present are primarily based on fixed or portable gas sensors (hardware based) in ammonia cold storages [14,15]. By detecting the life-threatening ammonia concentrations, the gas sensors can warn the technical staff of the leak and help to start the ventilation systems in cold storages. However, this gas sensing method has a number of limitations which include the following: (a) It usually takes a few minutes for the sensors to response [16], which may not be timely for escaping; (b) The price of sensors with good gas selectivity is high. Most of the high-performance sensors involve irreversible reactions and need to be replaced regularly. These add to the cost of using them; (c) The locations where the sensors are installed do not correctly indicate the accurate leak locations. In view of the above-mentioned facts, further researches on leak detection methods used in ammonia cold storages are necessary.

The real-time leak detection methods applied in pipelines have been developed and investigated in the past decades in petroleum, chemicals, gas and municipal water systems. These methods include pressure point analysis [17], real time modeling method [18–20], negative pressure wave analysis [21], statistical method [22] and so on. They are effective ways to continually, practically and dynamically monitor pipelines. Among these methods, the real-time modeling methods, which exploit hydraulic behavior of the pipe flow to build a mathematical model and estimate typical pressure loss and flow rate difference, have good accuracy and sensitivity [13]. Basically, the real-time modeling methods can be mainly divided into two categories: transient and steady-state. If the real-time modeling methods are truly to be implemented in ammonia pipelines in cold storages, a few points should be mentioned: (a) It is possible to be a responsive real-time detecting system; (b) It is not a highly complicated system for users to understand; (c) It is cost-efficient for application and maintenance. However, the transient models have the disadvantage of being very expensive and complex for the use of extensive instruments [23]. Therefore, the steady-state modeling method may be a cost-efficient and simple way to detect the pressurized liquid ammonia pipeline in cold storages.

The one-dimensional steady-state flow model of pipeline can be used to detect the leak by solving mass-balance, momentum-conservation and energy-balance equations. Baghdadi and Mansy [24] experimentally and theoretically investigated this model and proposed a leak location method. They provide a great insight into the increase in the static pressure profile (i.e., a down-stream pressure increase, relative to the pressure just up-stream the leak location) occurring at the leak location. But in their method the size and flow coefficient through the leak point needs to be known, which may be impossible in practical use. In the present study, a real-time modeling method based on steady-state pipe flow is proposed and tried for use in liquid ammonia pipeline in cold storages. A leak indicator σ is introduced based on the one-dimensional steady-state flow model, and the leak occurrence is detected by comparing σ with a threshold value σ_{Le} (which was obtained under leak-free conditions). A locating algorithm is proposed based on the pressure difference profile along with the length of the pipeline as well as the increase in the static pressure just at the leak point. Experiments of liquid ammonia leaks and R22 leaks are carried out to analyze the performance of the leak detection method. It is found that this method can detect and locate the leak with relatively good performances. What's more, it is a simple yet sensitive method which can be extended to the application of detecting the liquid ammonia pipeline in cold storages.

2. Method

In the following section the principle of the leak detection is presented, and a locating algorithm is provided. A procedure for detecting is also given for a single leak point detection of the pressurized liquid refrigerant pipelines.

2.1. Principle of the leak detection

The system under consideration is depicted schematically in Fig. 1(a). There is a rupture with unknown diameter located at the distance of L_e from the inlet. The pressure and flow rate are measured in real-time at the inlet and the outlet of the pipeline to check the leak and to estimate the location.

The detection system follows some objective and subjective features. (a) The detection focuses on the pressurized liquid refrigerant pipeline, which is operating at low and medium pressure, with lengths up to a few hundred meters. This means that incompressible fluid properties are assumed (i.e., ρ is constant). The relatively short distance of the pipeline, in which the negative pressure caused by the leak moves so quickly, enables the pressure and flow rate change with good consistency [25]; (b) Adiabatic flow in the pipeline is assumed because the polyurethane foam insulation is adopted outside of the pipeline; (c) This study is focused on the pressurized liquid refrigerant pipeline, which is operating at low pressure (about 0.03 MPa, gauge pressure) and wrapped in a thick insulation layer. The pressure reduction may not be significant with a leak, and the released liquid ammonia is blocked by the insulation layer. Thus, a two-phase flow would not exist in the pipeline when leak occurs is supposed; (d) One-dimensional flow is assumed.

By applying the conservation equations of mass and momentum to the adiabatic and incompressible flow through the pipeline, if there is no leak, the following equation is obtained:

$$\frac{\partial P}{\partial x}+\frac{\rho f v|v|}{2D}=0 \tag{1}$$