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A method for simulating the entire leaking process and calculating the liquid leakage volume of a damaged pressurized pipeline

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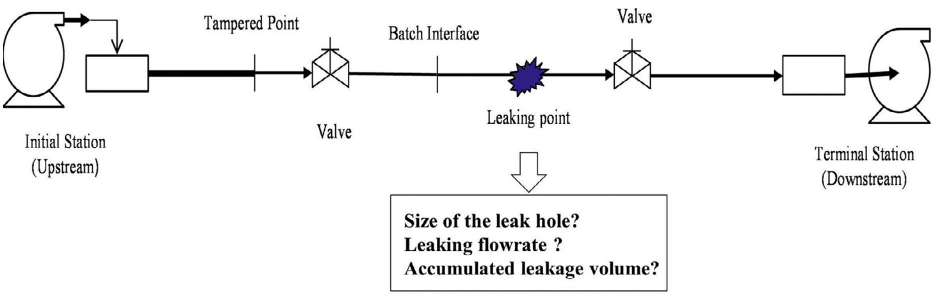
HIGHLIGHTS

- The liquid leakage volume during the entire pipeline leaking process is calculated.
- The entire leaking process is divided into 4 stages based on transient pressure.
- The critical parameters affecting the leakage volume are analyzed.
- The models' practicality and accuracy are validated by real leaking experiments.

GRAPHICAL ABSTRACT



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ABSTRACT

The accidental leakage of long-distance pressurized oil pipelines is a major area of risk, capable of causing extensive damage to human health and environment. However, the complexity of the leaking process, with its complex boundary conditions, leads to difficulty in calculating the leakage volume. In this study, the leaking process is divided into 4 stages based on the strength of transient pressure. 3 models are established to calculate the leaking flowrate and volume. First, a negative pressure wave propagation attenuation model is applied to calculate the sizes of orifices. Second, a transient oil leaking model, consisting of continuity, momentum conservation, energy conservation and orifice flow equations, is built to calculate the leakage volume. Third, a steady-state oil leaking model is employed to calculate the leakage after valves and pumps shut down. Moreover, sensitive factors that affect the leak coefficient of orifices and volume are analyzed respectively to determine the most influential one. To validate the numerical simulation, two types of leakage test with different sizes of leakage holes were conducted from Sinopec product pipelines. More validations were carried out by applying commercial software to supplement the experimental insufficiency. Thus, the leaking process under different leaking conditions are described and analyzed.

1. Introduction

With the aging of the super pipeline system, accidents, like fluid leaking, happen frequently due to damage to the pipe structure itself because of corrosion, structural or third party damage [1–3]. Flammable or explosive matter easily leads to considerable

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Nomenclature

a	velocity of pressure wave in the pipeline (m/s)
$a_{o,i}$	the pressure wave propagation velocity in oil o in pipeline segment i (m/s)
A, A_{pipe}	cross-sectional area of the pipeline (m^2)
A_L	the area of leaking hole (m^2)
c	specific heat capacity of the oil (J/(kg °C))
C_0	coefficient of leaking hole, $C_0 = aC_dA_L$, dimensionless
C_d	orifices flow coefficient, 0.98–0.99, dimensionless
d_4	oil relative density, dimensionless
d_4^{20}	oil relative density at the temperature of 20 °C, dimensionless
D	the inner diameter of the pipeline (m)
D_i	the inner diameter of pipeline segment i (m)
$D_{orifice}$	the diameter of the orifice (m)
e	specific internal energy of the oil (J/kg)
E_i	the Young's modulus of pipeline segment i (Pa)
f	frictional coefficient along the pipeline, dimensionless
g	gravitational acceleration (m/s^2)
h	specific enthalpy of the oil (J/kg)
H	the pressure head in pipeline (m)
H_L	the initial pressure head at leaking point (m)
H_0	the pressure head outside leaking hole (m)
H_{air}	head of local air pressure (m)
H_{vapor}	head of oil saturated vapor pressure (m)
k_o	oil elastic modulus of batch o (Pa)
K	overall coefficient of heat transfer (W/(m^2 °C))
L	total length of the pipeline (m)
L_r	the distance between the start of the pipeline and the leaking point (m)
$L_{sat\text{-}L}$	the length of the pipeline from saturation point to leaking point (m)
p	the pressure in the pipeline at leaking point (Pa)
Δp_d	the change of pressure in pipeline at leaking point during Δt (Pa)
Δp_s	the change of pressure at upstream station during Δt (Pa)
Δp_e	the change of pressure at downstream station during Δt (Pa)
ΔP	the pressure drop between the upstream and downstream at leaking point (Pa)
q_H	heat flux between oil and pipeline internal face (W/m^2)
Q_L	the instantaneous leakage flowrate (m^3/s)
ΔQ	the change of flow rate between the upstream and downstream at leaking point (m^3/s)
s	the elevation difference of the two adjacent calculating nodes (m)
t	time (s)
T	the temperature of the oil in the pipeline (°C)
T_0	surrounding environmental temperature (°C)
v	average velocity of the oil in the pipeline (m/s)
x	the distance from the upstream station (m)
z, Z	the elevation of the pipeline (m)
z_L	the relative elevation at the leaking point (m)

Greek symbols

α	flow contraction coefficient, 0.62–0.66, dimensionless
α_p	inflation coefficient of the oil(1/°C)
β	ratio of two kinds of oil density, $\beta = \rho_A/\rho_B$ dimensionless
γ	coefficient of temperature for calculating viscosity (1/°C)
δ_i	the thickness of pipeline segment i (m)
ζ	coefficient of temperature, dimensionless
θ	the included angle between the leaking segment and horizontal direction (rad)
λ	Darcy friction coefficient, dimensionless
ξ	coefficient of resistance, depending on the structure, opening and caliber, dimensionless
ρ	average density of the oil in the cross-sectional area (kg/m^3)
ρ_o	oil density of batch o (kg/m^3)
ν_1, ν_2	oil viscosity at the temperature of T_1 and T_2 (m^2/s)
ψ	weighting factor, $0.5 < \psi < 1$, dimensionless

Subscript

p	pipeline
L	leak point
sat	saturation point
i	distance node
j	time node

negative impact on the local environment and residents nearby can cause economic losses when there is leakage from the damaged pipelines [4–6].

A number of leaking cases have been presented to raise awareness of the range of hazards during the pipeline leaking process. Most previous studies focused on the leak detection and localization [7–12] of oil, gas, water or CO_2 in the transportation pipeline. Others concentrated on the diffusion or dispersion of released fluid into the air, soil or water leaked from pressurized pipelines or vessels [13–18]. Further studies have introduced the method to assess the related risks [5,6,19–21] or the sustainable response strategies [22] to prevent, minimize, control or mitigate leaking fluid hazards. However, the calculation of the leakage volume during the period of unsteady or steady state leaking remains under investigated. Existing methods were implemented through experiment or statistics to give a rough calculation result of the quantity of leakage.

After leakage has occurred, the recommended immediate action under all circumstances is to isolate the leaking section of the pipeline, i.e. to activate the ESD (emergency shut down) valve upstream and any intermediate valves upstream/downstream of the leakage point [23]. Experimental studies were developed by using dimensional analysis to determine the relation between the leak rate and the parameters, such as size of orifice, fluid properties and operational parameters when the liquid ejected from the leakage orifice [23–25]. However, more attention has been paid to the efflux coefficient or empirical formula than the leakage volume.

To calculate the quantity of leakage volume quickly and directly, the leaking process was simplified as one-dimensional steady effluent from a nozzle stub and the transient leaking rate and accumulated volume were calculated using the Bernoulli equation [26–28] whether pipe flow exists or not. This method can be used to calculate the leak rate during the static leaking process after activating the ESD valve but it is not applicable to real long-distance pipelines because of the unknown fluctuant pressure at the leaking point. To improve the accuracy and investigate the unsteady state leaking process, a differential equation model has been applied in numerical simulations [24,29,30]. The leaking process is simulated as liquid spills from a short pipe segment through a cracked point to the main flow region especially from the selected pipeline's cross-section to its outside area. Because of the influence of axial flow and the pipeline's elevation, this model could not be used to simulate