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Three-dimensional numerical simulation of non-condensables accumulation induced by steam condensation in a non-vented pipeline

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Abstract

A substantial increase of the concentration of non-condensable gases in the mixture with steam can occur in a non-vented pipeline due to the condensation. This phenomenon is investigated with the thermal-hydraulic and physicochemical code HELIO. The hydrogen and oxygen accumulation is simulated and analyzed for a real non-vented steam pipeline of the nuclear power plant. The results show the propagation of non-condensables concentration front, the temperature and velocity field of the steam–non-condensables mixture, and the velocity and thickness of the condensate that drains on the pipeline's inner walls. The gas mixture temperature is verified with measurements from a full size test facility. The presented modelling approach and numerical results are unique regarding the simultaneous solution of the heat and mass transfer in the system consisting of the steam–non-condensable gases mixture and the thin liquid film on the pipe's wall.

Keywords: Condensation; Hydrogen; Non-condensable; Accumulation; Numerical simulation; HELIO

1. Introduction

Certain amounts of hydrogen and oxygen are present in coolants of light water nuclear reactors during the normal operation. They are mainly produced by the radiolytic water decomposition [1]. The hydrogen and oxygen concentrations in non-vented steam pipelines could be further substantially increased due to the steam condensation. The condensed steam is drained, while the concentration of remaining non-condensable hydrogen and oxygen increases. The operational experience of nuclear power plants has shown that even an explosive mixture of hydrogen and oxygen could be reached. Recently, this phenomenon caused two incidents of hydrogen and oxygen explosion at auxiliary systems of the Boiling Water Reactor (BWR) plants, in November 2001 in the Hamaoka plant in Japan [2] and one month latter in the Brunsbuettel plant in Germany [3,4].

The hydrogen and oxygen accumulation within non-vented steam pipelines is driven by coupled thermal-hydraulic and diffusion transport phenomena, such as the steam condensation in the presence of non-condensables, the condensate drainage, the non-condensables absorption at the liquid film surface, and the non-condensables transport by diffusion in the gas mixture with steam and by gas mixture convection. The steam–non-condensables gas mixture convection is induced by the replenishment of the condensed steam volume with the inflowing fresh steam–non-condensables mixture, by the temperature and concentration induced buoyancy forces and by the gas mixture shear at the moving liquid film surface. After several days, weeks or even months (depending on the heat loss to the surrounding atmosphere, which determines the condensation rate) an explosive hydrogen–oxygen mixture could

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Nomenclature

A	area, m^2
a	interfacial area concentration, m^{-1}
c_p	specific heat, $J\,kg^{-1}\,K^{-1}$
D	diffusion coefficient, $m^2\,s^{-1}$, pipe diameter, m
D_h	hydraulic diameter, m
f	friction coefficient
g	mass fraction, gravity, $m\,s^{-2}$
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$, specific enthalpy, $J\,kg^{-1}$
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
M	molar mass, $kg\,kmol^{-1}$
n	indicator of straight pipe ($n = 1$) or elbow ($n = 2$) in Eqs. (2) and (4)
p	pressure, Pa
p_c	partial pressure of gas mixture component, Pa
q_A	heat flux, $W\,m^{-2}$
R	radius of the pipe curvature (Fig. 2), m
Re	Reynolds number
r	radial coordinate, m
T	temperature, K, °C
t	time, s
u, v, w	velocity components, $m\,s^{-1}$
V	volume, m^3
x	coordinate, m

Greek symbols

α	volume fraction
Γ_{con}	rate of condensation, $kg\,m^{-3}\,s^{-1}$
Γ_a	rate of absorption, $kg\,m^{-3}\,s^{-1}$
δ	liquid film thickness, m
θ	circumferential coordinate, rad
λ	latent heat of condensation, $J\,kg^{-1}$
μ	dynamic viscosity, $kg\,m^{-1}\,s^{-1}$
ρ	density, $kg\,m^{-3}$
σ	surface tension, $N\,m^{-1}$
τ	shear stress, $N\,m^{-2}$

Subscripts

atm	parameter of the surrounding atmosphere
c	non-condensable component of the gas mixture
CV	control volume
H_2	hydrogen
i	liquid film surface, gas mixture–liquid film interface
in	insulator
O_2	oxygen
w	wall
σ	related to surface tension
1	liquid film
2	gas mixture

Abbreviations

BWR	boiling water reactor
CMFD	computational multi-fluid dynamics
NPP	nuclear power plant
RHRS	residual heat removal system

be formed, providing a risk for eventual hydrogen explosion and destruction of components integrity. At the plant the presence of the radiolytic gases is monitored by a number of temperature measurements located at non-vented pipelines' segments, devices and vessels where the radiolytic gases accumulation is expected [3]. Namely, the increase of radiolytic gases concentration decreases the steam partial pressure and consequently decreases the saturation temperature and steam–radiolytic gases mixture temperature. Although a substantial experience with the mechanisms of radiolytic gases accumulation is gained in the past, there are still unresolved questions and uncertainties about the possibilities and dynamics of these processes [3].

After the incidents in the Hamaoka and Brunsbuettel plants corresponding investigations have been performed. The non-condensable radiolytic gases accumulation in the non-vented steam pipeline in the Residual Heat Removal System (RHRS) of the Hamaoka Nuclear Power Plant was investigated at the 1:1 scaled experimental test facility [2]. For safety reasons, hydrogen is replaced by helium as a light gas that has similar molar weight and diffusion coefficient. The initial concentration of helium and oxygen in steam was 100 and 1000 times higher than in the real plant conditions in order to speed up the accumulation process. The non-condensables accumulation was detected with 143 thermo-couples along the pipeline inside. Results of the non-condensables accumulation and a possibility of the concentration front formation at several locations along the pipeline are presented in [2]. Pipeline's vertical segments and bends are indicated as possible locations of concentration fronts, and the non-condensables are accumulated in the volume of pipeline from the concentration front to the upper closed end. Required time periods for the concentration front propagation up to certain presented locations are not reported, neither are information about the dynamics of concentration front propagation along the pipeline. The non-condensables accumulation in the three-dimensional geometry of the RHRS pipeline was also numerically simulated with the one-phase computational fluid dynamic (CFD) model of the commercial code STAR-CD. In this modelling approach the steam condensation in the presence of non-condensables is taken into account through the mass sink term in the mass and momentum conservation equations. The condensate presence, drainage and influence on the gas mixture flow due to the gas mixture–condensate liquid film interfacial drag were not taken into account. One conservation equation for the mole concentration of the mixture of hydrogen