Nuclear Engineering and Design 326 (2018) 183–189

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Study on the passive refrigeration for main control room of nuclear power plant in power outage accident

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ARTICLE INFO

Keywords:
High pressure air
Passive cooling strategy
Throttling refrigeration
Expansion refrigeration
Main control room of nuclear power plant

ABSTRACT

High-pressure air with room temperature can be used for refrigeration through isentropic expansion or isenthalpic throttling process with no power supplying, which can also meet the demands of oxygen supplying for operators in the insulated situation. Two passive cooling strategies for high-pressure air are proposed: one is throttling refrigeration, and the other is expansion refrigeration, which can provide an effective method to ensure the safety of operators in main control room when an emergency occurs in nuclear power plant. Comparisons between the two passive cooling strategies are done by theoretical and experimental methods, and the cooling effects for both strategies are analyzed. The results show that the passive cooling strategy of isentropic expansion can meet the both requirements of cooling and clean air supplying for the main control room when emergencies occur in nuclear plants, with the minimum cooling capacity of 3000 W.

1. Introduction

Since the accident of Fukushima nuclear power plant has been happened, how to ensure the safety of nuclear power plant has become the most concerned issue. In the case of an accident, the main control room can exclude the harmful radiation and supply clean air for the people inside the room, which can temporarily provide a safe space for operators. To enable people inside the room to survive, there must have a comfortable indoor temperature and sufficient oxygen in the main control room (Wouters et al., 1998). For the most advanced AP1000 nuclear power plant, the technology of cooling storage by the concrete structure is used for emergency air conditioning (Sutharshan et al., 2011). However, this technology was hardly implemented in existing nuclear power plants because there were so many reconstructions need to be done to increase the thickness of concrete structures and to embed the metal parts into these concrete structures. And for this technology, outside air needed to be introduced into the main control room for the purpose of ventilation after 72 h, and the radioactive gas may be introduced at the same time to endanger the people in the main control room (Lee et al., 2013).

Now the main control room of the nuclear power plant cooling system is generally used in the central air conditioning, once the power failure, it will not work. The main control room of AP1000 nuclear power plant is to provide a place to meet the requirements of earthquake resistance and habitability, so that the operator can monitor the whole nuclear power plants in the full operation of the nuclear power plant life cycle, including the emergency operation. The temperature of the main control room of the nuclear power plant should be maintained at 25 C, so that the body feels comfortable. The tem M.K. Sapra et al. (2015) proposed that Fukushima nuclear accident promoted the development for advanced reactor's passive safety system. T.L. Schulz (2006) analyzed the project of Westinghouse Electric, AP1000, in details, which was the two-loop pressurized water reactor and also the updated version of AP600. Lee et al. (2013) presented the optimization design to improve passive cooling stress analysis, which was used for AP1000 shield building to protect nuclear plant of steel vessels. Sato and Kojima (2007) proposed various changes of passive containment systems of boiling water rector in the future, and it can make use of the ventilation opening of second containment on the operation dome to release containment pressure. Chang et al. (2013) presented a kind of IPSS, which had passive decay heat removal system, passive safety injection system, and passive containment cooling system, etc. Dong et al. (2012) proposed the evaluation model of residence in master-control room of the second generation China's advanced nuclear plant. F.R. Siddiqui et al. (2014) conducted the economic analysis for a solar powered refrigerating cycle system with mixed storage and absorption.

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https://doi.org/10.1016/j.nucengdes.2017.11.022
Received 14 December 2016; Received in revised form 20 June 2017; Accepted 10 November 2017

Nomenclature

μ_J	coefficient of adiabatic throttling
T	fluid temperature
P	pressure
h	indicates the isenthalpic condition.
c_p	gas specific heat at constant pressure
v	gas specific volume
R	gas constant
T_1	gas temperature before expansion
T_2	gas temperature after expansion
p_1	gas pressure before expansion
p_2	gas pressure after expansion
r	adiabatic coefficient.

Zio and Pedroni (2010) developed the subset simulation method to analyze the key parameters of passive cooling system's uncertainty, which is beneficial to improve the sensitivity of the system. Cho et al. (2013) proposed the simulation for heat dissipation potential of the current PAFS of the third generation nuclear plant in the condition of incident.

Therefore, for the case of emergency power off of main control room in AP1000 nuclear power plants, two passive cooling strategies for high-pressure air with room temperature are proposed by authors: one is throttling refrigeration, and the other is expansion refrigeration. These two programs have not really applied to the main control room of AP1000 nuclear power plant, only in the experimental stage. The cooling effects for both strategies are tested by experiments, and the results show that the passive cooling strategy of isentropic expansion can meet both requirements of cooling and clean air supplying for the main control room when emergencies occur in nuclear plants (Park et al., 2012).

2. Working principle and theoretical analysis

2.1. Working principle

The high pressure air stored in the air tank is used as the refrigerant in this passive cooling system of the main control room. High-pressure gas is cooled through a throttling or expander machine. The cold air passes a heat exchanger to extract heat of the room, then flows into the main control room to meet both requirement of cooling and clean air supplying for the operators.

2.2. Theoretical analysis

2.2.1. Theory of throttling refrigeration

The actual process of gas throttling is irreversible. There are no heat exchanges and net work exchanges between the system and ambient during the throttling process, so the enthalpy of gas would decrease change continually and the entropy would increase, but the temperature variation is not certain (Lovatt, 2014).

The temperature variation of gas after adiabatic throttling can be described by the formulation (1.2.1) (Zeng et al., 2002; Yezheng, 2004; Wang et al., 2003):

$$\mu_J = \left(\frac{\partial T}{\partial P}\right)_h \tag{1.2.1}$$

where

- μ_J – coefficient of adiabatic throttling;
- T – fluid temperature;
- P – fluid pressure;
- h – indicates the isenthalpic condition.

The differential equation of enthalpy is:

$$dh = c_p dT - \left[T\left(\frac{\partial v}{\partial T}\right)_p - v\right]dp \tag{1.2.2}$$

Combining Eqs. (1.2.1) and (1.2.2), the coefficient of adiabatic throttling becomes:

$$\mu_J = \left(\frac{\partial T}{\partial P}\right)_h = \frac{1}{c_p}\left[T\left(\frac{\partial v}{\partial T}\right)_p - v\right] \tag{1.2.3}$$

And the actual gas equation is:

$$\left(p + \frac{a}{v^2}\right)(v - b) = RT \tag{1.2.4}$$

Substituting Eq. (1.2.4) into Eq. (1.2.3), the coefficient of adiabatic throttling can be expressed as:

$$\mu_J = \frac{(2a/RT)(1-b/v)^2 - b}{c_p[1-(2a/vRT)(1-b/v)^2]} \tag{1.2.5}$$

When $\mu_J = 0$, the equation of conversion curve can be obtained:

$$T = \frac{2a}{9Rb}\left(2 \pm \sqrt{1 - \frac{3b^2}{a}p}\right)^2 \tag{1.2.6}$$

where

- h – gas enthalpy;
- c_p – gas specific heat at constant pressure;
- v – gas specific volume
- R – gas constant
- a,b – constants of Van der Waals equation (Shen and Tong, 2007). $a = 0.1358\ \mathrm{m^6 \cdot Pa/mol^2}$, $b = 0.\ 0364 \times 10^{-3}\ \mathrm{m^3/mol}$.

When $\frac{\partial P}{\partial T} = 0$, the maximum pressure of conversion can be obtain *ed*: $P_N = \frac{a}{3b^2}$ .Substituting the constants of a, b into theP_N equation, the value of $P_N = 34.2$ MPa can be obtained finally.

The analytic result indicates that for the method of throttling refrigeration, the cooling effect can be achieved as long as the pressure of compressed air is lower than 34.2 MPa, the temperature is 132.55–650 K.***

2.2.2. Theory of expansion refrigeration

Expander is a machine which utilizes compressed gas to expand to export mechanical work, and the gas temperature would reduce during the expansion process, so the cooling effect can be achieved. As we all know, the gas with a certain pressure and temperature has a certain amount of energy which is called internal energy.

According to the law of energy conversion and conservation, the gas enthalpy can certainly reduce during the process of isentropic expansion in the expander. The cooling effect can be achieved by the intensely temperature decreasing of the gas in the expander, and the more the expander works, the more the air temperature decreases (Kovačević et al., 2006).

The equation of isentropic expansion process of ideal gas is written as (Petitpas and Aceves, 2014):

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{r-1}{r}} \tag{1.2.7}$$

where

- T_1 – gas temperature before expansion;
- T_2 – gas temperature after expansion;
- p_1 – gas pressure before expansion;