A Bounding Evaluation of Minimum Steam Venting Capacity in Reactor Coolant Gas Vent System Design for APR1400

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1. Introduction

In APR1400 design, the Reactor Coolant Gas Vent System (RCGVS) is required to provide a safety-grade means of remotely venting non-condensible gases from the Reactor Vessel Closure Head (RVCH) and the pressurizer (PZR) steam space during post-accident conditions when large quantities of non-condensible gases may collect in these high spots. In addition, the RCGVS is required to provide a safety-grade means of remotely removing steam from the RVCH and the PZR steam space for pressure control purposes during post-accident conditions in the event that failures preclude the use of PZR main and auxiliary spray systems.

Quantitative non-condensible gas venting capacity requirement has been provided in EPRI-URD[1] as follows: The RCGVS shall have sufficient capacity to vent one-half of the RCS volume in one hour with the vented volume expressed in standard cubic feet of gas over the range of venting conditions considered, assuming a single failure. From previous evaluations and depressurization tests, it has been demonstrated that non-condensible gas venting capacity is enveloped by steam venting capacity for pressure control in natural circulation cooldown (NCC) analysis.

In this paper, a bounding calculation methodology is developed to provide the minimum steam venting capacity for pressure control in NCC analysis for the system design of APR1400 RCGVS. In the methodology, of bounding calculations, are introduced so-called Fanno Flow Model (FFM) where steam venting process is assumed as an adiabatic frictional compressible gas (saturated dry steam) venting phenomena as well as Homogeneous Equilibrium critical flow Model (HEM) where steam venting process is assumed as adiabatic frictional two-phase mixture (steam mixture) venting phenomena. The developed methodology will be utilized to estimate the minimum steam venting capacity for NCC analysis and to evaluate the impact of flow restricting orifice installation in the RCGVS design

2. Development of Bounding Calculation Methodology

In compressible gas flow in a constant area duct, there are two ideal flow models such as Fanno Flow Model (FFM) defined as adiabatic flow with friction and Rayleigh Flow Model (RFM) defined as flow with heat transfer but without friction. For adiabatic compressible gas flow in a constant area duct, the FFM is utilized to estimate saturated dry steam venting capacity. The relationship of total system resistance to inlet Mach number is presented based on the FFM as follows [2]:

$$KT_{eff}(\mathrm{Ma},\gamma)=\left(\frac{1-Ma^2}{\gamma\cdot Ma^2}\right)+\left(\frac{\gamma+1}{2\cdot\gamma}\right)\cdot\ln\frac{(\gamma+1)\cdot Ma^2}{2+(\gamma-1)\cdot Ma^2} \quad (1)$$

Here, γ is ratio of specific heat. The effective pipe length, L_{eff}, can be determined by using the total system resistance based on the standard pipe, KT_{eff} , as follows:

$$L_{eff}=KT_{eff}\cdot\frac{d_s}{f_s} \quad (2)$$

Here, d_s is inner diameter of pipe, and f_s is friction factor of pipe. In the FFM theory, the above effective length of standard pipe means the pipe length required to develop the duct flow from inlet Mach number to the sonic point (Ma=1) where the exit flow is sonic. For subsonic inlet compressible gas flow, the Modified Darcy Formulas (MDF) [3] had been developed by using the FFM as standard engineering practice to estimate the discharge flow rate of compressible fluid such as hydrogen, air and dry steam. These MDF are very convenient to understand the characteristics of compressible gas venting process since the formula is the relationship between pressure drop (ΔP) and flow rate (W or Q) with total system resistance (KT) and net expansion factor to compensate for property changes during venting process.

For adiabatic frictional two-phase mixture (steam mixture) venting cases, two-phase steam mixture critical flow and pressure drop models are used to estimate steam mixture venting capacity. Here, steam is assumed to be not saturated dry steam as ideal gas but steam mixture with frozen quality resulting from adiabatic vapor expansion during venting. For the adiabatic vapor expansion discharges, the Frozen Homogeneous Flow (FHF) models as a kind of HEM critical flow model had been developed to address the thermal non-equilibrium effects such as flashing or condensing during adiabatic depressurization or expansion discharges[4][5]. From comprehensive review of two-phase critical flow models [4~6], it is found that the FHF model developed by Starkman et al. is a special case of Henry and Fauske's generalized FHF model and the most adequate and simple model for an adiabatic vapor expansion discharge case. The FHF model of Starkman et al. can be expressed as follows: [4]

$$G_{c\_FHF}=\rho_{mc}\cdot\sqrt{\frac{2\cdot P_o\cdot x_{ec}}{\rho_{go}}\cdot\frac{\gamma}{1+\gamma}} \quad (3)$$

where,

$$\rho_{mc} = (1 - x_{ec}) \cdot \frac{1}{\rho_{fo}} + \frac{x_{ec}}{\rho_{go}} \cdot \left(\frac{2}{1+\gamma}\right)^{\frac{1}{1-\gamma}} \quad (4)$$

The above FHF model is very convenient to estimate two-phase critical flow rate explicitly as a function of critical pressure (P_c) and inlet stagnation properties. Generally, the FHF model increase the critical flow rate and therefore provides improved and bounding answers to thermal non-equilibrium conditions. However, the FHF model cannot treat the impact of complicate geometry configuration on the pressure drop such as overall system resistance from the stagnation point to the choking point including entrance, pipe friction, exit and other form losses. In fact, in the FHF model, the wall shear forces are assumed to be negligible in momentum balance equation and an isentropic vapor expansion is assumed in a converging nozzle or a short length orifice to determine the critical pressure ratio.

Therefore, the two-phase flow pressure drop model to treat the impact of geometry is required to adequately apply the FHF model to the choking point. As the choking point in the FHF model, a convergent and divergent exit pipe was assumed and the critical pressure ratio, P_c/P_o was simply determined by gas dynamics for isentropic expansion process. For steam as the ideal gas with γ = 1.3, the critical pressure ratio (P_c/P_o) can be obtained as 0.55 from the above equation.

Differently from the FFM, the two-phase mixture critical flow model assumes that a choking point occurs at the smallest flow areas instead of the exit of piping system. As such, the choking zone of the long pipe system is supposed as the singularity point ($dG_m/dP=0$) of homogeneous equilibrium two-phase flow pressure drop model (HE-PDM) and the imaginary inlet point of the choking zone is assumed as L = 40 D upstream of choking point. As a two-phase mixture pressure drop model to account for all pressure losses from the stagnation point (reservoir condition) to the imaginary inlet point, the well-known HE-PDM can be utilized for two-phase mixture flows of $G_m \geq 2000$ kg/m^{2}s (409 lbm/ft^{2}s) as follows:

$$\Delta P_{in\_out} = {G_m}^2 \cdot \left(\frac{1}{\rho_{m_{out}}} - \frac{1}{\rho_{m_{in}}}\right) + {\varphi_{go}}^2 \cdot \frac{f_{go} \cdot L}{d} \cdot \frac{G_m^2}{2 \cdot \rho_g} \quad (5)$$

where,

$$\frac{1}{\rho_m} = \frac{x_e}{\rho_g} + \left(\frac{1-x_e}{\rho_f}\right) = x_e \cdot v_g + (1 - x_e) \cdot v_f \quad (6)$$

$$\varphi_{go}^2 = \frac{v_f}{v_g} + x_e \cdot \left(1 - \frac{v_f}{v_g}\right) \quad (7)$$

3. Bounding Calculations using As-built Design Data

In Shin-Kori units 5 and 6 (SKN 5&6) RCGVS design, it has been decided that a flow restricting orifice is newly installed into the each vent path of RCGVS to limit flow rate due to new introduction of emergency reactor depressurization system (ERDS). Therefore, the influence of venting capacity on inclusion of the flow restricting orifice into each vent path is needed to be quantitatively evaluated.

The steam venting capacity of each vent path including the flow restricting orifice can be determined by the FFM or the MDF using the overall system resistance of each vent path. In this evaluation, the saturated steam is assumed to behave like a perfect gas. Therefore, there are no steam condensation and no choking at the orifice. The flow is assumed to choke at the exit of each vent path. This assumption is valid for subsonic venting cases of compressible fluids. However, the above approach is not valid for the cases that saturated steam is not ideal gas but steam mixture. In these cases, saturated steam can be allowed to be condensed by vapor expansion and a hypothetical break can be assumed to occur at the point just downstream of the orifice instead of the exit of each vent path. For these cases, the steam venting capacity of each vent path can be determined by the HEM with the HE-PDM. This approach is valid since saturated steams at higher venting pressures would be discharged as highly turbulent and two-phase dispersed mixture (mist) flows.

For the evaluation of steam venting capacity using the FFM or MDF as well as the HEM with HE-PDM, first of all, the flow resistance or each vent path is required to be estimated by well-known standard engineering practice [3] and [7] based on the Darcy formula using the as-built design data such as RCGVS isometric drawings. In this estimation, the flow through vent path is assumed to be fully turbulent and elevational effects on pressure drop are assumed to be negligible, since the venting flow velocities are high enough to develop fully turbulent flow and to neglect the gravitational effect. When calculating the system resistances or friction factors, where possible, the highest factors are assumed since it will maximize the overall system resistance to minimize the venting capacity.

In SKN 5&6 RCGVS design, as a flow restricting orifice, 7/32"x1" or 8/32"x1" long orifice is selected. Therefore, it can be concluded that a thick-walled (thick-edged) orifice model is more adequate than a thin-walled (square-edged) orifice model. For the case of inlet area (A_1) equal to outlet area (A_2) with throat area ratio ($\beta = \frac{d_o}{d_1}$), the flow resistance of orifice, K_o, is given by [7],

$$K_o = [0.5 \cdot (1 - \beta^2) + (1 - \beta^2)^2 + f \cdot \frac{L}{d_o}] \cdot \beta^{-4} \quad (8)$$

As shown in Fig. 1, the RCGVS connection to the PZR consists of 4 lines to the POSRV inlet lines. Physically, the flow rates at the connecting branch lines before merged to common header would be split with complex branch line partition law, which is governed by branch line configuration. For the calculation convenience and conservatism, it is assumed that there are four even branch flows with the system resistance (K_{1A}) of branch A, which is conservatively selected to consider a developing common header flow as shown in Fig. 2.

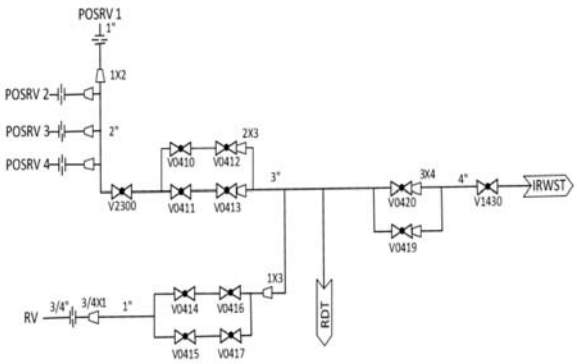

Fig. 1. RCGVS Configuration for SKN 5&6

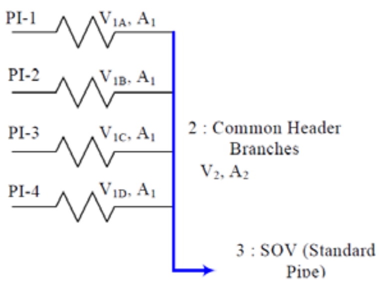

Fig. 2. Branch Flow Split Model for PZR Vent Path

As shown in Fig. 1, the RCGVS connection to the RVCH has one leading line with 3/4" and 1" sizes and then it is divided into two branch lines with 1" size and finally merged into one common line with 3" size. For calculation convenience and conservatism to maximize system resistance, it is assumed that there is one branch flow with the branch resistance (K_{2A}) as shown in Fig. 3. This assumption is valid since only one vent path will be selected during the RCGVS operation.

Flow resistances used in bounding calculations for each vent path, which are calculated by standard engineering practice using the as-built RCGVS isometric drawings of SKN 5&6, are summarized in Table 1. In this table, the standard pipe size of PZR vent path is 2 inches, while that of RVCH vent path is 1 inch. In addition, the inlet leading pipe size of PZR vent path is 1 inch, while that of RVCH vent path is 3/4 inch.

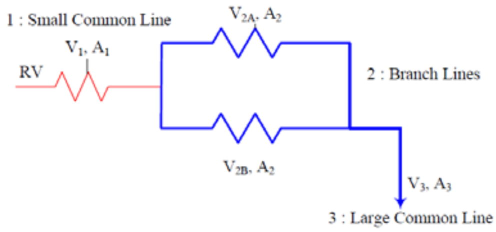

Fig. 3. Branch Flow Model for RVCH Vent Path

Table 1. Calculated Flow Resistance of Each Vent Path

Flow Resistance (K)	PZR Vent Path	RVCH Vent path
Partial K from Inlet Nozzle to Orifice (based on Standard Pipe Size)	344.1	144.6
Partial K from Inlet Nozzle to Orifice (based on Inlet Leading Line Size)	298.5	46.6
Total Flow Resistance (based on Standard Pipe Size)	365.8	198.6

In the bounding calculations, the steam mass flow rate leaving the flow restricting orifice is determined by two methods such as the FFM and the HEM. As mentioned above, in the FFM method, the choking point is assumed to be not the orifice but the exit of RCGVS, and steam is assumed to be ideal gas with a specific heat ratio (γ) of 1.3. Therefore, the steam venting capacity is determined by using the overall system resistance of RCGVS. On the other hand, in the HEM method, the hypothetical break is assumed to occur at the point just downstream of the orifice and the choked flow rate through the orifice is determined by utilizing the FHF model and the HE-PDM using the partial system resistance of RCGVS up to the orifice. The steam venting capacities of each vent path, which are calculated by both methods, are summarized in Table 2.

Table 2. Calculated Steam Venting Capacity for Each Vent Path

Venting Pressure (psia)	Calculated Results for PZR Vent (lbm/hr)		Calculated Results for RVCH Vent (lbm/hr)	
	FFM	HEM	FFM	HEM
2,500	19,063.4	23,836.2	5,990.8	9,084.1
2,000	15,474.0	18,115.8	4,862.8	6908.1
1,500	11,821.2	13,128.9	3,714.9	5,008.0
1,000	8,080.8	8,551.3	2,539.4	3,264.8
500	4,206.1	4,240.9	1,321.8	1,619.7

From the above calculation results, it can be seen that the steam venting flow rates based on the HEM method are 1.008 to 1.516 times greater than those of the FFM method. The reason why these results are derived can be addressed as follows. In the FFM method that saturated dry steam is assumed to be ideal compressible gas and the choking always occurs at the exit. On the other hand, the HEM (especially FHF) model considers steam quality change from the dry condition (x_o=1) to the frozen quality (x_e<1) based on a partial condensation caused by isentropic vapor expansion. In other words, the HEM method predicts a steam mixture denser than a dry steam, and thus increases critical mass flow rate. Furthermore, an intentional early choking at the flow restricting area (throat area) in the HEM method may increase the critical mass flow rate if the pressure drop through the orifice is not sufficient to avoid a subsequent choking in the downstream flow. From this modeling difference, it can be concluded that the HEM predictions are usually higher than those of the FFM. In general, the prediction differences between the HEM and the FFM can be reduced when the imaginary choking point for the HEM model is valid as the actual choking point and the choking condition stays in the downstream flow going to the exit. From this observation, it can be concluded that the HEM method for PZR vent path is more appropriate than that for RVCH vent path to evaluate the role of flow restricting orifice as the actual choking point, which is considered as a singularity point in the two-phase pressure drop model.

As shown in Table 2, it can be seen that the higher the venting pressure, the greater the difference between the HEM and the FFM methods. This trend can be explained by examining the frozen quality for a partial condensation caused by isentropic expansion of steam venting as shown in Table 3.

Table 3. Frozen Quality Change by Isentropic Steam Expansion in HEM Method

Venting Pressure (psia)	Frozen Quality for PZR Vent Path	Frozen Quality for RVCH Vent path
2,500	0.791	0.803
2,000	0.850	0.860
1,500	0.893	0.904
1,000	0.929	0.938
500	0.958	0.968

From this table, it is found that the increasing effect of steam mass flow rate due to a steam mixture discharge with frozen quality is faded out if venting pressure is decreasing.

4. Conclusion

In order to estimate the minimum steam venting capacity for NCC analysis and to evaluate the impact of flow restricting orifice installation in the APR1400 RCGVS design, the bounding calculation methodology has been developed based on the FFM for compressible gas venting and the HEM (especially FHF) for two-phase steam mixture venting.

In the bounding calculations using the as-built design data such as RCGVS isometric drawings, the steam mass flow rates leaving the flow restricting orifice were determined by two methods such as the FFM and the HEM. From the bounding calculation results, it can be concluded that the steam venting capacity estimated from the FFM or the MDF has been recommended as a lower bound value of actual steam venting flow rate. In this methodology, the actual steam venting flow rate was assumed to be between the FFM (or MDF) prediction as lower bound and the HEM (especially FHF) prediction as upper bound. Actually, this lower bound value has been confirmed by NCC analyst whether it is valid or not as the minimum requirement for NCC analysis. Finally, the minimum steam venting capacity requirements have been determined by NCC analyst and provided as the interface requirement for system design of RCGVS.

In addition, the impact of flow restricting orifice installation in the RCGVS design was well evaluated by utilizing the bounding calculation methodology developed in this paper. In particular, the thick-walled orifice model has a major role to increase overall system resistance in the FFM, which results in significant reduction of steam venting capacity, while it has a different role as an imaginary choking point for the HEM method.

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