Study on thermal-hydraulic phenomena identification of passive heat removal facilities

J. Y. Park*
Korea Institute of Nuclear Safety, Thermal-Hydraulic Research Dept., 19 Guseong-dong Yuseong-gu, Daejeon 305-338, KOREA
**Corresponding author: k385pjy@kins.re.kr*

1. Introduction

Recently, passive heat removal facilities have been integral features of new generation or future reactor designs worldwide. This is because the passive heat removal facilities depending on a natural force such as buoyancy can give much higher operational reliability compared to active heat removal facilities depending on pumped fluid flow and as a result they can decrease core damage frequency of a nuclear power plant drastically ever achievable before. Keeping pace with this global trend, SMART and APR+ reactors also have introduced passive heat removal features such as a passive residual heat removal system (PRHRS) and a passive auxiliary feed water system (PAFS) in their designs.

Since many thermal-hydraulic (T-H) phenomena including steam condensation are involved during operation of the passive heat removal facilities, they ought to be properly simulated by T-H codes such as MARS-KS and RELAP5 in order to guarantee reliable safety analysis by these codes. Unfortunately, however, these T-H codes are not well validated with respect to phenomena related to passive heat removal mechanism because previous focus on these codes validation was mainly on the LB LOCA and resulting phenomena. To resolve this gap, Korea Institute of Nuclear Safety has initiated a research program on the development of safety analysis technology for passive heat removal facilities. The main target of this program is PRHRS and PAFS in SMART and APR+ reactors and through this program, validation of capability of existing T-H codes and improvement of codes regarding passive facilities analysis are to be sought. In part of this research, T-H phenomena important to passive heat removal facilities (PRHRS and PAFS) are investigated in the present study.

2. Evaluation of previous PIRTs on passive heat removal facilities

Instead of identifying T-H phenomena regarding PRHRS and PAFS from scratch, they are deduced from various phenomena identification and ranking tables developed before. PIRTs used in the present study include SMART PIRT [1], APR+ PIRT [2], AP600 PIRT [3] and PIRT delivered by an IAEA document [4].

2.1 SMART PIRT

As a formal document of SMART design certificate process, Korea Atomic Energy Research Institute submitted a PIRT [1] for SMART reactor. Since it is a comprehensive PIRT encompassing all possible design basis accidents and their effects on various primary safety criteria, identified T-H phenomena in SMART PIRT [1] are general in nature. Therefore, in the present study, only T-H phenomena with direct relevance to PRHRS of SMART reactor are chosen. They are given by

- Natural convection in emergency cooling tank
- Stratification in makeup tank
- Condensation heat transfer in heat exchanger
- Natural circulation through piping and valve.

Since PRHRS plays an important role in cooling of residual heat of reactor, all of above T-H phenomena are chosen regardless of importance level determined by the original document [1].

At the beginning of operation of PRHRS, mixing between saturated or superheated vapor from steam generator and subcooled stagnant water in PRHRS piping cannot be avoidable and as a result condensation induced water hammer phenomena may generate [5]. This phenomenon also may occur at PAFS of APR+ reactor because the same passive mechanism applies. Therefore, water hammer effect is identified additional T-H phenomenon.

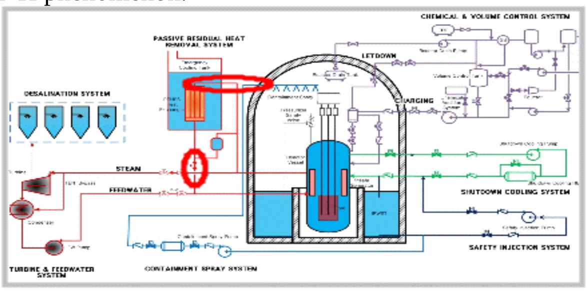

Fig. 1. Possible location of condensation induced water hammer (horizontal red circle)

2.2 APR+ PIRT

Recently, APR+ PIRT [2] was developed by nuclear industry expert panels as a part of APR+ reactor development program. Depending on various event sequences of feed line break accident, importance and knowledge levels of T-H phenomena were identified. Since APR+ PIRT [2] was developed focused on PAFS itself, its result is utilized in the present study without any modification. However, importance and knowledge levels are re-adjusted on a conservative basis. Part of T-H phenomena deduced from APR+ PIRT is given below.

Table I: T-H phenomena through APR+ PIRT

Comp.	Sub-comp.	Phenomena	Importance	Knowledge
Heat exchanger	Inlet header	Condensation	2	4
		Flow distribution	3	3
	Tubes	Condensation HT	5	4
		CIWH	3	3
		Flow stratification	4	3
		NC gas behavior	3	3
		Flow instability	4	2
		Flow regime of elbow	4	2
		HT change inside tube	2	3
	Outlet header	NC gas behavior	3	3
		Condensation	1	4
PCCT		Subcooled boiling	5	5
		Pool boiling	5	5
		1 phase natural circ.	5	5
		2 phase natural circ.	5	3
		Local CHF	3	2
		Fouling effect	1	5
		Bundle effect	4	2

		Flashing	3	5
		Mixture level	3	5

2.3 AP600 PIRT

AP600 reactor is different from SMART and APR+ reactors in aspects that full featured passive systems are implemented and its PRHRS is mainly operated under single phase condition. Nevertheless, PRHRS of AP600 reactor has a kind of similarity to passive heat removal facilities of SMART and APR+ reactors. For example, IRWST in PRHRS of AP600 is very similar to ECT in PRHRS of SMART and PCCT in PAFS of APR+. And a heat exchanger in PRHRS of AP600 is comparable to that of SMART and APR+. Having these facts in mind, AP600 PIRT [3] developed for SB LOCA, MSLB and SGTR accidents is reviewed and T-H phenomena which have direct relevance to SMART and APR+'s passive heat removal facilities are identified. For heat exchanger, it is found that 5 out of 8 T-H phenomena suggested by AP600 PIRT [3] are direct relevance to SMART and APR+'s passive heat removal facilities. They are as follows:

- Condensation at tube side of heat exchanger
- Flow resistance within heat exchanger tube
- Heat transfer between heat exchanger and IRWST
- Degradation of heat transfer due to non-condensable gas effect at heat exchanger tube
- Voiding(plugging) due to non-condensable gas within heat exchanger

As for IRWST, it is found that 7 out of 9 T-H phenomena of AP600 have direct relevance to SMART and APR+'s passive heat removal facilities. They are given as below:

- Flashing in discharge line of IRWST
- Flow and temperature distribution around heat exchanger's tube bundle within IRWST
- Interphase condensation within IRWST
- Overall natural convection within IRWST
- Level of IRWST
- Heat transfer from IRWST fluid to surroundings through IRWST tank wall
- Thermal stratification within IRWST

Although a flashing is not likely to occur at ECT or PCCT of SMART or APR+ reactors, it is included as a T-H phenomenon because it may occur at downstream of a system initiation valve of PRHRS or PAFS in another form of water hammer (i.e. low pressure discharge) at the beginning of passive heat removal facilities. (See, vertical red circle in Fig.1.)

2.4 Comparison with IAEA TECDOC-1624

IAEA TECDOC-1624 [4] published by IAEA includes T-H phenomena about various passive safety features of almost all new reactors developed worldwide at present times. Since "passively cooled steam generator natural circulation" of their classification category corresponds to passive heat removal facilities of SMART and APR+ and since "passively residual heat removal heat exchanger" category corresponds to AP600's PRHRS, T-H phenomena suggested by IAEA TECDOC-1624 [4] for above two categories are compared to those identified through SMART PIRT, APR+ PIRT and AP600 PIRT. Through comparison, it is found that 4 T-H phenomena suggested by IAEA TECDOC-1624 [4] which is given below,

- Behavior in large pool of liquid
- Effect of non-condensable gases condensation heat transfer
- Natural circulation
- Behavior emergency heat exchangers and isolation condenser,

are included in T-H phenomena identified in the present study.

3. Development of consolidated thermal-hydraulic phenomena on passive heat removal facilities

Based on above evaluations about various PIRTs, total 12 T-H phenomena related to PRHRS in SMART and PAFS in APR+ reactors are identified according to newly suggested definition of phenomena. (See, Table II). Definition, basis, source, importance and knowledge level, related reactor type, location of occurrence, validation level and method for each T-H phenomenon are also given in a research report [6] in detail.

Table II: Consolidated T-H phenomena

Phenomenon	Definition
Voiding effect	Plugging of flow path by non-condensable gas
Non-condensable gas effect	Degradation of heat transfer at heat exchanger tube surface due to non-condensable gas
Condensation heat transfer	Condensation wall to fluid heat transfer and interphase condensation heat and mass transfer
Water hammer	Condensation induced water hammer and flashing induced water hammer (low pressure discharge)
Natural convection	1ϕ & 2ϕ natural convection within ECT (SMART) and PCCT(APR+) including flow and temperature fields
Natural circulation	Overall circulation flow rate and its stability
Level	Level variation of ECT(SMART) and PCCT(APR+)
Flow regime change	Flow pattern variation in horizontal tubes of PAFS heat exchanger(APR+)
Centrifugal effect	Flow pattern variation and heat transfer augmentation at tube side of helical steam generator(SMART) due to centrifugal force
Flow resistance	Pressure drop increase within helical coil tube of steam generator(SMART)
Heat loss	Heat transfer from fluid to surroundings through wall of ECT(SMART) and PCCT (APR+)
Fouling effect	Degradation of heat transfer capability due to fouling of heat exchanger tube of SMART and APR+

4. Conclusion

12 T-H phenomena direct relevance to PRHRS and PAFS of SMART and APR+ reactors are identified by reviewing previous PIRTs. These phenomena will be used as bases of validation and improvement of current T-H codes such as MARS-KS and RELAP5 for safety analysis of passive heat removal facilities.

REFERENCES

[1] KAERI, KAERI/TR-3780/2009, 2009.
[2] KAERI, Minutes for APR+ PAFS PIRT meeting, 2010.
[3] USNRC, NUREG/CR-6541, 1997.
[4] IAEA, IAEA TECDOC-1624, 2009.
[5] KINS, KINS/GR-378, 2007.
[6] KINS, KINS/RR-815, 2011.