Journal of the Korean Nuclear Society
Volume 19, Number 2, June, 1987

Derivation of Subcompartment Heat Transfer Correlation from HDR Tests

Un Chul Lee
Seoul National University
(Received February 12, 1987)

HDR 실험에 근거한 격납용기 구분방내의 열전달 상관식 도출

이 은 철
서울대학교
(1987. 2. 12 접수)

Abstract

Statistical evaluation for the heat transfer correlation in the containment subcompartments is carried out from HDR experimental data. Heat transfer data for three HDR blowdown tests, V.42, V.43 and V.44, are analyzed to deduce the correlation. As Uchida already proposed, air-to-steam density ratio is proven to be the most affecting parameter in this study. Here Uchida heat transfer correlation is revised by including temperature difference between the atmosphere and the wall surface, and atmospheric pressure. In addition to these dependencies, atmospheric turbulence and time factor may be included in the model. This implication, however, is not successful, because turbulence and transient phenomena were not adequately quantified in the HDR program. It is concluded that a strong correlation exists between the heat transfer coefficient and temperature differences, specially for forced circulation conditions.

초 록

격납용기 구분방 내에서 정확한 열전달 상관식을 얻기 위해 HDR 실험 자료들을 통계적인 방법으로 분석하였다. 세가지의 blowdown 시험, 즉 V.42, V.43 and V.44를 통해 얻어진 열전달 자료들이 상관식을 유도하는데 사용되었다. 이미 Uchida에 의해 제안되었던 air-to-steam 질량비는 이 실험에서도 역시 가장 중요한 인자로 입증되었다. 이 연구에서는 Uchida의 열전달 상관식으로 만족되지 않은 실험자료들을, 격납용기 대기와 벽 표면의 온도차의 함수로, 또 대기 압력의 함수로 표시하여 수정하려고 시도하였다. 이 종속성외에도 대기의 난류도와 시간에 따른 인자가 고려되어야 한다. 그러나 HDR 계획에서는 흐름속도의 측정 자료가 부정확하기 때문에 정량적인 관계식의 유도는 힘들다. 다만 열전달 계수와 온도 차이의 관계가 밀접하다는 사실을 밝혔으며 특히 강제순환 조건에서 더욱 이 관계는 명백해짐을 볼 수 있다.

I. Introduction

For the containment analysis, there are few large-scale simulations for commercial power plant conditions. This is because of tremeneous expenses in doing such simulations. In Germany, one of the large-scale tests furnishing reliable data on the containment analysis was conducted at the Battele-Frankfurt facility.[1] In this experiment, highly pressurized water was employed as the blowdown fluid. Since then, Battele-Frankfrut experimental data base became the standards for which most of containment analytical models and calculational procedures were benchmarked. However, these data revealed inaccuracies and limited use of narrow range because of insufficient data base. As a consequence, models derived from Battele-Frankfurt tests showed over-estimation of pressure in the break compartment, inaccurate pressure gradients between break compartment and the adjoining compartments, and large carryover fraction of suspended water.[2] Recent simulation carried out in Germany in this area is called HDR (Heiss Dampf Reaktor, Superheated Steam Reactor) program. This facility was rebuilt from existing BWR plant for compartmental analysis. Major purpose of this program is to improve understanding reactor system behavior under the loss-of-coolant accident conditions and to define margins of safety correctly. Also it is to evaluate and improve design and testing technique for nlucear systems and components. Lot of important characteristics have been examined through this series of HDR program. They are transient short-time pressurization in the break compartment at the onset of blowdown, transport phenomena of air and steam flow according to compartmental pressure differences, and heat transfer mechanism between flowing atmosphere and the wall surface (Fig. 1). In this research, however, relatively long-term behaviors in the heat transfer mechanism are mainly analyzed. Short-term (<2 sec) characteristics are reported in detail in the reference 3. These evaluations are based on the heat flow between the subcompartment atmosphere and wall surface on specially designed blocks. By analyzing HDR data base, the result may be utilized to modify existent heat transfer

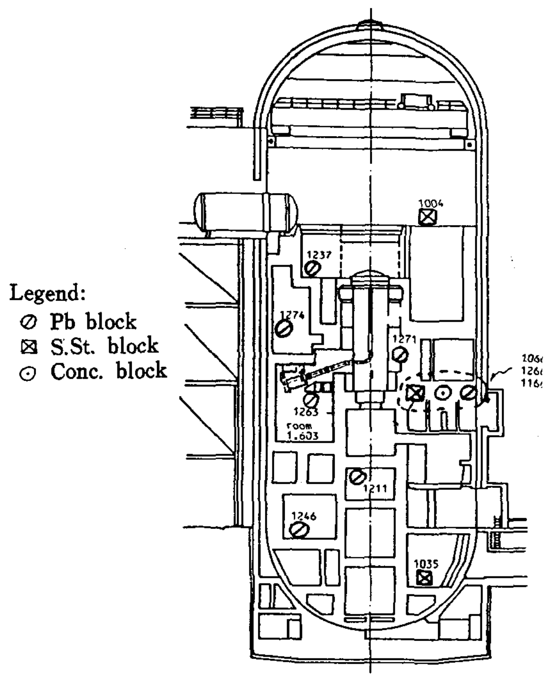

Fig. 1. Shematic of Heat Transfer Measurement Locations inHDR Containment

models and to further understand the blowdown phenomena.

II. Functional Dependencies on Heat Transfer Coefficient

Inside the containment, there are two-components, two-phase fluids. There exist air in the containment and steam and water from blowdown (Fig. 2). In reality heat transfer mechanism is determined by so many complex variables. Parameters which influence heat transfer coefficient are estimated as the followings: relative air-to-steam density ratio, atmospheric turbulence, temperature difference between atmosphere and containment wall surface, heat sink geometry, atmospheric pressure, etc. Among these parameters, air-to-steam density ratio was proposed by Uchida[4] as a single major dependency on heat transfer coefficient. This derivation is, in fact, turned out to be very good estimation by many

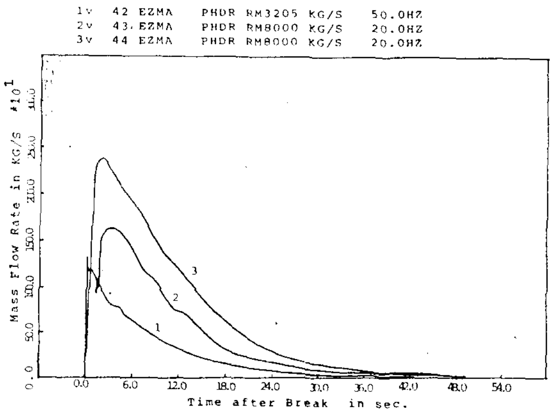

Fig. 2. Mass Flow Rates for HDR Experiments

authors.[5,6] Researchers tried to find out what else influence heat transfer. For example, at the onset of blowdown, air-to-steam density ratio is quite large. In this situation, Uchida's estimation becomes quite off the experimental values. This means that the turbulency in the flowing atmosphere plays important role. Through HDR program, atmospheric flow velocities were measured at selected locations. These measurements, however, could not be related to the flowing velocity due to lack of data and due to inadequate measuring locations. Thus atmospheric turbulence still remained as the major uncertainty. Meanwhile temperature difference between atmosphere and wall surface are estimated as another important parameter. In the HDR program, atmospheric temperatures were measured well at the selected locations in the subcompartments. In the past the temperature was also assumed as one of the important parameters, but the dependency was not clarified quantitatively yet. Heat transfer characteristics may also vary according to the flow geometry. Flow geometry includes the geometry of the energy transfer surface and the geometry of the flow field in front of the surface. Specially when integral energy transfer rates should be utilized in the analysis, surface average properties become important. This geometric factor is not easy to quantify in the heat transfer model. Finally atmospheric pressure has been considered as a dependent parameter on heat transfer coefficient. However, this pressure dependency is considered relatively weak. This behavior may be confirmed by a careful statistical analysis from the HDR measured data. Unfortunately this kind of evaluation cannot be done straight-forward, because time dependency of pressure is closely related to time dependency of atmospheric turbulence. So the turbulent behavior may overshadow the influence of pressure transient. In this research, however, since the atmospheric turbulence cannot be quantified, the atmospheric pressure takes the role for the turbulence instead.

III. Statistical Evaluation of HDR Data

The HDR experimental data are analyzed statistically to determine a significant relationship between the heat transfer coefficient and parameters describing the physical state of the atmosphere and heat transfer surface. The first parameter chosen is the air-to-steam density ratio. The dependency is expected from theory and previous experimental data. For example, the Uchida's correlation can be approximated by:

$$H = 379(\rho_a/\rho_v)^{-0.707} \quad (1)$$

where H is the heat transfer coefficient and (ρ_a/ρ_v) is the air-to-steam mass ratio. HDR data also show that air-to-steam mass ratio is one of the most important parameters. Using routines from the IMSL9[7], best regression for the HDR data was obtained with two separate sequences of analysis. In the first sequence an attempt is made to isolate the effects of geometry and location. To achieve this the data for 3 experiments (V42, V43 and V44) at the same location are grouped as a set. This yields 11 sets of data, each corresponding to a measurement location (Fig. 1 and Table 1). In the second, the influence of the important (ρ_a/ρ_v) ratio is minimized by

Table 1. Comparison of the Sets adopted in this paper and the HDR Compartments.

Data Set No.	HDR Room No.
1	1035
2	1246
3	1211
4	1263
5	1066
6	1266
7	1166
8	1271
9	1274
10	1237
11	1004

Table 2. Evaluation of Parametric Dependencies on the Heat Transfer Coefficient for Each Compartment*

Data Set	a	b	c	log A
Set 1	−0.792	−0.548	2.166	3.016
Set 2	−0.622	−1.238	3.005	3.713
Set 3	−1.327	−1.441	−0.025	5.544
Set 4	−0.432	−0.713	2.241	3.020
Set 5	−0.490	−1.222	3.053	3.573
Set 6	−0.588	−1.448	3.536	3.522
Set 7	−0.408	−1.224	2.216	3.262
Set 8	−0.485	−0.899	−0.284	3.714
Set 9	−0.649	−0.899	0.116	3.387
Set 10	−0.496	−0.387	1.067	3.155
Set 11	−0.870	−1.544	0.984	5.204

*$H=A\ (\rho_a/\rho_v)^a\ (\Delta T)^b\ (P)^c$

selecting data points having similar ratios.

Results of the first analysis sequence are summarized in Table 2. As shown in the table the HDR data brackets the air-to-steam ratio dependency established by Uchida. The established correlation exponent varies from −0.4 to −1.33. This variation is due to location (geometry) and thus turbulence level dependent. In general, the importance of the (ρ_a/ρ_v) ratio is seen to vary inversely with the turbulence level. This can be deduced by considering the data sets yielding the largest negative exponent. Data set 3 has the value of −1.33 for 'a'. It is the only measured location placed in a "dead end" passage with no possibility of flow through atmospheric streams. Turbulence reaches this location only through eddy diffusion. Sets 1 and 11 are at the opposite ends of the containment (cellar and dome). If these three locations are excluded, the (ρ_a/ρ_v) exponential dependence narrows into a range of −0.41 to −0.65. Note that Table 2 presents results of a 'best-fit' correlation[7] which includes also dependencies on ΔT $(=T_{\text{bulk}}-T_{\text{surface}})$ and dependencies on pressure. The statistical significance of these coefficients is considerably smaller.

For the second analysis sequence the air-to-steam mass ratios are sorted in x-array with increasing order for the entire available data set. The entire available (ρ_a/ρ_v) range is divided into 54 groups. The groups are then analyzed separately according to the following correlation equation: where

$$H_g=A_g(\rho_a/\rho_v)_g^a\cdot(\Delta T)^b\cdot(P)^c \tag{2}$$

where H_g=group average heat transfer, coefficient,

g=group number,

A_g=group constant,

$(\rho_a/\rho_v)_g^a$=group average air-to-steam density ratio,

ΔT=temperature difference between the atmosphere and the surface, and

P=compartment pressure.

Equation (2) can be rewritten as

$$H_g=B_g^*\cdot(\Delta T)^b\cdot(P)^c, \tag{3}$$

where

$$B_g^*=A_g\cdot\overline{(\rho_a/\rho_v)}_g^a.$$

The evaluation for these dependencies is shown in Table 3. It is preferrable to take the air-to-steam mass ratio range as small as possible. A total of ~6,000 data points are available in the evaluation. Data for the first 10 seconds are discarded to reduce the time dependent initialization effects. Then groups are chosen for the density ratio so that each contains 100 data

Table 3. Dependencies of Temperature Difference on Heat Transfer Coefficients within Small Air-to-Steam Mass Ratio Range.

Group No.	Air-to-Steam Mass Ratio Range	Avg. Gr. Ratio	*b*	*c*	B_g*
1	0.001~0.022	0.012	−0.753	1.036	4.200
2	0.023~0.040	0.030	−0.780	1.111	4.143
3	0.040~0.059	0.050	−0.753	1.176	4.082
4	0.059~0.090	0.073	−0.859	0.778	4.292
5	0.090~0.143	0.113	−1.187	−0.267	4.740
6	0.145~0.200	0.172	−0.690	2.975	3.328
7	0.200~0.291	0.246	−0.804	1.958	3.631
8	0.293~0.358	0.326	−1.056	0.974	4.106
9	0.358~0.430	0.396	−0.901	0.877	3.918
10	0.432~0.543	0.489	−0.834	2.261	3.436
11	0.543~0.623	0.583	−0.942	1.623	3.660
12	0.624~0.727	0.680	−0.797	2.174	3.313
13	0.727~0.839	0.780	−0.743	2.326	3.214
14	0.839~0.963	0.902	−0.752	1.958	3.255
15	0.966~1.052	1.005	−0.781	2.151	3.225
16	1.053~1.172	1.118	−0.609	1.965	3.012
17	1.173~1.353	1.258	−0.685	1.657	3.109
18	1.362~1.515	1.435	−0.620	1.457	3.062
19	1.515~1.671	1.585	−0.680	2.008	2.934
20	1.673~1.777	1.731	−0.738	1.718	3.076
21	1.777~1.932	1.852	−0.584	1.931	2.895
22	1.932~2.102	2.022	−0.443	1.698	2.807
23	2.102~2.284	2.199	−0.334	−0.091	3.113
24	2.287~2.431	2.357	−0.246	0.086	2.991
25	2.439~2.604	2.517	−0.265	−0.320	3.036
26	2.604~2.776	2.684	−0.298	−0.273	3.043
27	2.776~2.889	2.836	−0.235	−0.090	2.968
28	2.892~3.007	2.955	−0.190	−0.147	2.753
29	3.007~3.105	3.059	−0.099	−0.546	2.718
30	3.105~3.196	3.150	−0.148	−0.863	2.881
31	3.198~3.388	3.289	−0.206	−0.377	2.852
32	3.388~3.482	3.438	−0.021	−1.333	2.770
33	3.485~3.621	3.562	−0.074	−0.548	2.642
34	3.621~3.769	3.693	−0.331	0.972	2.628
35	3.772~3.958	3.871	−0.428	0.872	2.805
36	3.961~4.221	4.069	−0.402	0.211	2.921
37	4.223~4.664	4.458	−0.236	−0.550	2.734
38	4.695~5.056	4.870	−0.095	−0.996	2.594
39	5.056~5.431	5.254	0.032	−1.313	2.455
40	5.431~5.839	5.640	−0.009	−0.543	2.353
41	5.847~6.076	5.966	−0.082	1.020	2.117
42	6.076~6.253	6.178	0.023	0.774	1.968
43	6.253~6.544	6.384	0.028	0.121	2.041
44	6.544~7.240	6.846	−0.146	0.260	2.341
45	7.264~8.032	7.656	−1.710	−0.085	4.894

Group No.	Air-o-Steam Mass Ratio Range	Avg. Gr. Ratio	b	c	B_g*
46	8.043～ 8.759	8.429	−1.767	−0.104	4.928
47	8.763～ 9.870	9.263	−1.774	0.648	4.719
48	9.871～11.041	10.423	−1.052	0.945	3.396
49	11.054～13.626	12.125	−3.048	3.025	5.978
50	13.639～17.640	15.240	−2.236	1.631	4.883
51	17.646～22.248	19.864	−0.586	−0.705	2.828
52	22.261～24.697	23.576	−0.567	−1.034	2.775
53	24.698～27.071	25.752	−1.267	0.745	3.245
54	27.088～31.211	28.836	0.307	−0.418	1.298

points. The group range and group average air-to-steam density ratio are also tabulated in Table III. From this table, we can draw the following conclusions.

1. If the air-to-steam mass ratio is small ($<\sim2.0$), the exponent for the temperature difference is fairly constant between -0.7 and -1.0.

2. For the larger ratio groups (up to ~7.0), the exponents fall down to almost zero. This means that temperature difference may not play a role in this range in comparison with effects of other variables.

3. For the much larger groups, dependencies are very inconsistent. This inconsistency may be explained as follows:

   a. The data are sparse and scattered so that the best correlation cannot be obtained. And the the group interval is much larger.

   b. Most of the larger air-to-steam mass ratio occur in the beginning of blowdown. So turbulence may affect more dominantly.

4. From Table 3, factorization of group averaged density ratio results

$$B_g^* = 1488 \cdot \overline{(\rho_a/\rho_v)}^{-0.725}.$$

This proves that Uchida correlation predicts the heat transfer coefficient very well with only air-to-steam density ratio. The constant is quite larger than that in Uchida's prediction. This is explained by including the dependency of temperature difference in this model.

IV. Discussions

By analyzing HDR experiments, major parameters to determine the heat transfer coefficient are assumed as air-to-steam density ratio, temperature differences between the compartment atmosphere and wall surface, atmospheric pressure, and turbulency or time. Through statistical analysis of HDR data base, it is proven that air-to-steam density ratio is the most important parameter, as Uchida proposed. However, the analysis also suggests that temperature difference be another factor to determine the heat transfer coefficient and atmospheric pressure have a relatively weak dependency. According to HDR programs, atmospheric turbulence is considered as one of affecting parameters on heat transfer. However, this contribution cannot be quantified to deduce the correlation. In this statistical analysis, we can draw the following conclusions:

1. Heat transfer coefficient can be described by the following formula,

$$H = A \cdot (\rho_a/\rho_v)^a \cdot (\Delta T)^b \cdot (P_{atm})^c.$$

In the range of $0.5 < (\rho_a/\rho_v) < 6.0$, Uchida correlation is predicting heat transfer coefficient very well.

2. The exponent 'a' may vary between -0.6 and -0.8, which is close to Uchida's -0.707. However, the constant A is much larger than Uchida's. This is explained by including remaining variables, ΔT and P_{atm}.

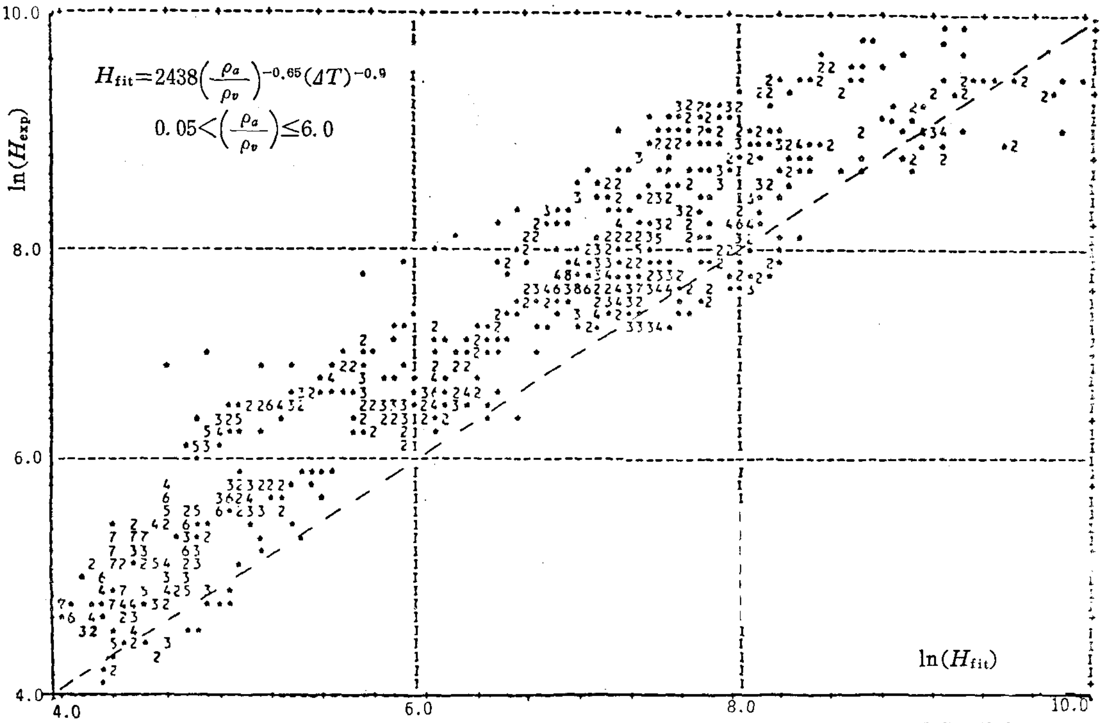

Fig. 3. Comparison between Experimental Heat Transfer Coefficients and Fitted Coefficients at $10<t<70$(numerics show the number of overlapped data)

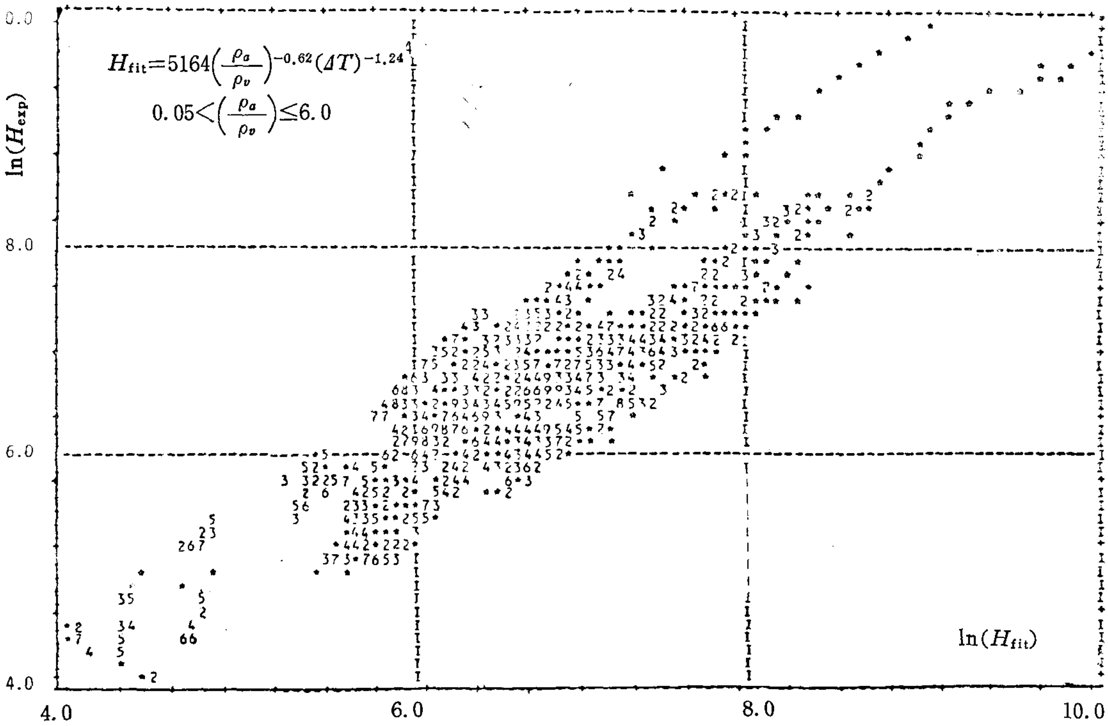

Fig. 4. Comparison between Experimental Heat Transfer Coefficients and Fitted Coefficients at $70<t<120$ (numerics show the number of overlapped data)

3. The exponent 'b' lies in the range of −0.7 and −1.0. This explains that temperature difference is affecting on the heat transfer (figs. 3 and 4).

4. Instead, atmospheric pressure in the compartment is not contributed in determining the heat transfer coefficient.

5. At the beginning of blowdown, turbulence must be taken into account.[8] This effort, however, could not be quantified because of lack of data base.

6. HDR data clearly show a strong time dependency, which may be assumed either with turbulence itself or with transient behavior of two-phase, two-component flow.[8] Presently there are not sufficient informations to model the time dependency adequately. So finally the heat transfer correlation is suggested to be

$$H=A(v,t)\cdot(\rho_a/\rho_v)^a\cdot(\Delta T)^b\cdot(P_{atm})^c.$$

V. Conclusion

Through analysis, the temperature difference between compartment atmosphere and wall surface is one of rolling parameters in subcompartmental heat transfer mechanism. Previously, Corradini[9] derived the condensation correlation by introducing temperature difference under the highly turbulent conditions. In this study, the dependency is rather relaxed with the dependency of turbulency, because HDR data base includes many different types of flow paths and different flowing conditions. So these dependencies must be determined through more sophiscated analysis. Correlation in this study separated the turbulent dependency with the temperature difference in the model. Further study is recommended to quantify turbulent phenomena, to improve the correlation.

References

1. "Die Containment-Versuchsanlage (C- und D-Versuche)", BR-RS 50-21-1 (Oct. 1978).
2. "Kurzzeitnachrechnungen Von Absolute- und Differenze-drucken der RS-50 Versuche", Reihe C, BF-RS 50-24-1 (May 1977).
3. Almenas, K., "Comparison of Experimental and Calculated Pressure Differences in the HDR Containment," PHDR-Arbeitsbericht Nr. 3.388/83 (Aug 1983).
4. Uchida, H., et al., "Evaluation of Post-Incident Cooling Systems of LWR's," Proc. Int'l Conf. Peaceful Uses of Atomic Energy, 13, 93, A'CONF: 28/P436, IAEA(1965).
5. Almenas, K., "Heat Transfer from Saturated and Superheated Atmosphere for Containment Analysis," Nucl. Sci. & Des., 71 (July 1982).
6. Croix, J.M. and Liegeois, A., "Study of Condensation of Steam and Air Mixtures in Transition," CEA Report T.T. No. 596 (NRC Translation 557) (Dec. 1978).
7. IMSL9, International Mathematical and Statistical Library, version 9 (1983).
8. Almenas, K. and Lee, U.C., "A Statistical Evaluation of the Heat Transfer Data Obtained in the HDR Containment Tests," US NRC Report after performed under NRC 04-84-004 (to be published).
9. Corradini, M.L., "Turbulent Condensation on a Cold Wall in the Presence of a Non-condensable Gas," Nucl. Tech., 64 (1984).