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# Assessment of Dryout Heat Flux Correlations for Particle Beds

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## ABSTRACT

To assess the coolability of particle bed, which is formed in reactor cavity, it is important to assess the prediction capabilities of Dryout Heat flux correlations. The existing DHF correlations (Sowa et al., Dhir-Catton (a), Dhir-Catton (b), Hardee-Nilson, Ostesen, Shires-Stevens, Lipinski, Jones et al., Dhir-Barleon, Theofanous-Saito, Henry-Fauske) for particle beds are assessed using developed DHF database. Eleven DHF correlations are chosen for assessment based on literature survey. Among them, five are based on flooding correlation, which are used for chemical engineering and others are based on conservation equations. The parameters in DHF correlations are directly substituted into correaltions. Totally 202 data are classified into 6 groups based on bed thickness and particle diameter. In each group, prediction capabilities of correlations are assessed and shown by standard deviation and root mean square (RMS) error. Prediction capability of each correlation depends on the data group and none of correlations shows best prediction capability on entire groups. According to present study, even if those correlations show poor prediction capability, Lipinski correlation is best correlation considering entire groups.

## 1. Introduction

When severe accident occurs in nuclear power plant, melting of core may occur and melted core materials may be relocated and released from reactor vessel to reactor cavity. Due to the in-vessel or ex-vessel contact with the coolant, melted core forms particulated debris bed. In ex-vessel phase, if the debris bed can not be cooled enough, the reactor cavity base mat will be penetrated by melted core. Therefore the assessment of debris bed coolability has been considered as important issue.

Debris bed coolability can be assessed using the balance of heat generation in the debris and heat removal rate from the debris. The heat generation rate is determined by the decay heat level and the fraction of fuel components in the debris. In addition it is determined by oxidation heat of metal components in debris. Because the decay heat level and chemical energy of the metal oxidation are well known, major uncertainties in the heat generation is debris composition. However, major uncertainties of the debris bed coolability are due to the heat removal from the debris. Heat removal from debris is varied with debris configuration and the contact mode with water. If the molten core spreads over the reactor cavity well and makes shallow bed whose depth is less than the critical pool depth (about 10 cm) [1], debris can be cooled naturally. If debris is fragmented sufficiently and makes particle bed, and if particle bed characteristics is specified, then debris bed coolability is predicted by dryout heat flux models.

In this view point, it is very important to find out the suitable DHF correlation applicable to the severe accident condition. Up to now, several DHF correlation have been suggested based on mechanistic model and the experimental data, and correlation assessments have been performed. However, previous analysis simply consider all of the available DHF data and perform simple correlation assessment.

Considering the various severe accident conditions, the particulated debris bed has various conditions, i.e. particle diameter, bed depth, porosity, etc. Therefore, in present study, various regions with different particle diameter and bed depth are considered and we assess correlations in each region. As a results the best correlations are suggested according to regions.

## 2. Correlations, Data Bases and Assessment Method

There are several DHF correlations, suggested for particle bed as shown in Table 1. Sowa et al., Ostesen, Dhir-Barleon, Theofanous-Saito, and Henry-Fauske correlations are based on flooding correlations from the chemical industry that predict the flooding velocities in packed columns. Most of eleven correlations, except Hardee-Nilson correlation, suppose that heat is removed from the bed solely by vaporization of the coolant. Therefore they presuppose that the coolant is at saturation point and do not consider subcooling effect. Only Hardee-Nilson correlation regards subcooling effect, but all of the experiments were performed at the saturation point. The other correlations are based on conservation low. In suggested correlations, the key parameters of coolant are density, surface tension, viscosity and heat of vaporization. And, those of particle bed are particle diameter, porosity, and bed height.

Table 1 Main Features of DHF Correlations

| CORRELATION | YEAR | LIMITATIONS | REMARKS |
|---|---|---|---|
| Sowa et al. | 1971 | Large particles | flooding |
| Dhir-Catton (a) | 1976 | deep-beds<br>small particles | gravity<br>liquid drag |
| Dhir-Catton (b) | 1977 | shallow-beds | linear function of bed thickness |
| Hardee-Nilson | 1977 | deep-beds | gravity<br>vapor and liquid drag<br>subcooling |
| Ostesen | 1979 | large particles | flooding |
| Shires-Stevens | 1980 | small particles<br>medium and deep-beds | gravity<br>capillary force<br>vapor drag |
| Lipinski | 1980 | small and large particles<br>medium and deep-beds | gravity<br>capillary force<br>vapor and liquid drag |
| Jones et al. | 1980 | Small particles<br>deep-beds | gravity<br>vapor and liquid drag |
| Dhir-Barleon | 1981 | large particles | flooding |
| Theofanous-Saito | 1981 | large particles | flooding |
| Henry-Fauske | 1981 | porosity = 40%<br>large particles | flooding |

The DHF database [2] used in correlation assessment are described in Table 2: Data are coolant, particle diameter, porosity, bed thickness, and measured DHF for saturated volume heated beds at atmospheric pressure. In FARO experiments [3], it was observed that the mass averaged mean particle diameter is varied between 2mm and 5mm, and experimental results of FITS experiments [4] show that the mass averaged mean particle diameter is varied between 1mm and 3mm without explosion, but data are very rare. Considering the above two experiments, the particle diameter ranges during severe accident may be varied between 1mm and 5mm. And experiments for 1mm to 5mm particles are required, for severe accident analysis. In addition, in real severe accident condition, particles with various diameters will be formed and will make a particle bed in which particle diameter is varied with bed depth. However, there are a few data about mixed particle bed, and more detailed experiments with mixed particles which can simulate severe accident are required.

For correlation assessment, experimental conditions are divided into 6 regions based on particle diameter and bed thickness. Table 3 summarizes data number and data name according to each region. The name of each region is given as (bed thickness)-(particle diameter). For particle size parameter, L, M and S represent "large", "medium" and "small", respectively. For bed thickness parameter, D and S represent "deep" and "shallow", respectively. For it is impossible to find the physical properties of saturated acetone at atmospheric pressure, the data related to acetone are dropped in table 3. In table 4, DHF data for small particles are divided to very small (VS) region and moderately small (MS) region again. For particle diameters are varied between 1mm and 5mm for corium quenching test, we assume medium particle region as 1mm to 5mm. Both side of medium particle region is small particle region (under 1mm) and large particle region (over 5mm). Because it is known that for the particles which are greater than 0.5mm flooding will dominate the DHF phenomena [5], small particle region is divided at 0.5mm. For bed thickness, if we only assume the steady state heat conduction, critical pool depth is about 100mm [1], so shallow bed and deep bed are divided at 100mm. Here, critical pool depth is the bed thickness that can be cooled by conduction through the bed and natural convection of coolant. If 150 tons of corium is released, and fully fragmented and spreads over about 67m$^2$ (YGN 3&4 cavity area) with 0.4 of porosity, then the bed thickness will be 370mm. So in real severe accident case, we can expected that deep bed will be formed on the reactor cavity.

Table 2 DHF Database for Saturated Volume-Heated Beds at Atmospheric Pressure

| Data Source | Coolant | Particle Dia. (mm) | Porosity | Bed Thickness (mm) | DHF (kW/m$^2$) | No. of Data |
|---|---|---|---|---|---|---|
| Gabor et al. | Water | 0.303 | 0.390 | 66 – 88 | 56 – 192 | 2 |
| | Sodium | 0.325 | 0.484 – 0.536 | 98 – 170 | 153 – 953 | 6 |
| Keowin | Water | 0.356 – 0.850 | 0.410 – 0.450 | 59 – 126 | 470 – 925 | 17 |
| Sowa et al. | Water | 0.315 – 0.715 | 0.400 | 55 – 263 | 134 – 855 | 14 |
| Dhir-Catton | Water | 0.356 – 0.819 | 0.390 – 0.450 | 30 – 89 | 196 – 860 | 15 |
| | Acetone | 0.356 – 0.900 | 0.380 – 0.450 | 13 – 194 | 65 – 305 | 28 |
| | Methanol | 0.356 – 0.848 | 0.380 – 0.440 | 25 – 80 | 45 – 210 | 13 |
| Squarer-Peoples | Water | 0.650 | 0.400 | 76 – 192 | 280 – 480 | 7 |
| Trenberth-Stevens | Water | 0.680 – 2.000 | 0.400 | 20 – 190 | 163 – 1287 | 32 |
| Gabor-Cassulo | Water | 0.385 – 1.095 | 0.383 – 0.407 | 180 – 450 | 133 – 376 | 9 |
| | Acetone | 0.385 – 1.095 | 0.394 – 0.406 | 180 – 300 | 52 – 146 | 7 |
| | Methanol | 0.385 – 1.095 | 0.380 – 0.407 | 180 – 300 | 97 – 197 | 7 |
| | Freon-113 | 0.385 – 1.095 | 0.384 – 0.408 | 180 – 300 | 43 – 106 | 7 |
| Barleon-Werle | Water | 0.258 – 15.88 | 0.373 – 0.473 | 30 – 130 | 117 – 4340 | 25 |
| | Freon-113 | 0.258 – 15.88 | 0.373 – 0.473 | 30 – 130 | 16 – 1080 | 23 |
| Squarer et al. | Water | 0.550 – 6.350 | 0.400 | 125 – 288 | 250 – 1420 | 11 |
| Somerton et al. | Water | 1.588 – 4.763 | 0.400 | 50 – 100 | 730 – 1900 | 4 |
| | Acetone | 1.588 – 4.736 | 0.400 | 50 – 400 | 140 - 385 | 15 |
| **Total** | | **0.258 – 15.88** | **0.373 – 0.536** | **13 – 450** | **16 - 4340** | **242** |

Table 3 DHF Database Divided by Bed Thickness and Particle Diameter

| Particle Size (mm) | 0 to 1 (S) | 1 to 5 (M) | 5 to 15.88 (L) | Note |
|---|---|---|---|---|
| Bed Thickness (mm) | Data Name & Number | Data Name & Number | Data Name & Number | Total Number |
| 0 to 100 (S) | 89 (S-S) | 37 (S-M) | 7 (S-L) | 133 |
| 100 to 450 (D) | 52 (D-S) | 14 (D-M) | 3 (D-L) | 69 |
| Total Number | 141 | 51 | 10 | 202 |

## 3. Results and Discussion

Table 4 summarizes the assessment results showing standard deviations and RMS errors. Each correlation shows different prediction capabilities according to physical geometry such as bed thickness and particle size. The detailed results are as follows.

(a) Region S-S: Lipinski correlation gives least but still large prediction errors. The flooding based correlations such as Sowa et al., Ostensen, Dhir-Barleon and Theofanous-Saito correlations predict as well, but have still large prediction errors. This shows that it is necessary to develop new correlation for this region.

(b) Region S-M: Lipinski correlation gives least but still little large prediction errors. The flooding based correlations such as Sowa et al., Ostensen, Dhir-Barleon and Theofanous-Saito correlations predict as well.

(c) Region S-L: Lipinski correlation is the best correlation in this region and shows excellent prediction capability. And, Henry-Fauske correlation gives good results too. But, in this region, there are only 7 data points and these are not enough to assess correlations, so the assessment results in this region is not reliable. However, as shown above Lipinski correlation shows best prediction capability in shallow bed region (S-S and S-M), so we can reason that the assessment results in S-L region is somewhat reliable.

(d) Region D-S: Theofanous-Saito correlation gives the least but still some large prediction errors. Ostensen and Dhir-Barleon correlations show similar prediction capability. These two are based on flooding.

(e) Region D-M: Sowa et al. correlation gives the best and excellent prediction capability. Ostensen, Dhir-Barleon and Theofanous-Saito correlation gives very small prediction errors too. These all are based on flooding.

(f) Region D-L: Sowa et al. correlation gives best prediction errors but errors are still some large. Floding based correlations such as Ostensen, Dhir-Barleon, Theofanous-Saito and Henry-Fauske correlation gives relatively good results, but prediction errors are still large. In this region there are only 3 data points, so reliable assessment can not be expected. However, the assessment results show same trend comparing with previous five regions, so relative assessment results of D-L region is somewhat reliable but we can not say accurate prediction capabilities in terms of statistics.

It is shown that, the correlations based on flooding correlation, shows best prediction capability in deep bed region. On the other side, Lipinski correlation shows best prediction capability in shallow bed region. Generally, the flooding correlation is for large particles, so it is expected that the DHF correlations based on flooding correlation is valid for large particles. Through this study, it is shown that flooding based correlations show best prediction capability in medium size particle region (1mm to 5mm) comparing with small and large particle size regions. According to Ostensen-Lipinski [5], the estimated particle size above which flooding will dominate is 0.48mm for water, 0.87mm for sodium, 0.30mm for acetone, 0.47mm for methanol and 0.21mm for freon. Flooding criteria are less than 0.5mm except the case of sodium. But DHF data for sodium coolant are only 6, so we can say flooding will be dominant over 0.5mm of particle diameter. Now, in table 4, small particle region is divided by two regions again, the very small region (VS) and moderately small region (MS). As a result, in the case of shallow bed, prediction errors are getting small as particle diameters getting large, as we expected. But, in the case of deep bed, prediction errors of moderately small particle region (MS) are always greater than that of very small region (VS). This result shows that flooding will dominate over 0.5mm in shallow bed, but it is not certain in a deep bed.

In over-all, Lipinski correlation shows the best prediction capability; usually it is marked at best correlation or top class correlations. Sowa et al., Ostensen, Dhir-Barleon and Theofanous-Saito correlations shows relatively good prediction over-all region. All of these correlations, except Lipinski correlation, are based on the flooding correlations. Hardee-Nilson [6] and Shires-Stevens correlations use linear relative permeability assumption, so they show relatively large prediction errors. But Lipinski correlation used more accurate relative permeability, so it shows relatively small prediction errors.

In DHF database, DHF values are varied as particle materials are varied, although particle diameter, porosity, bed thickness and coolant properties are same. The reason is that the effect of capillary force is depends on the contact angle between the particle and liquid, and this contact angle is depend on material properties and surface conditions [8], so DHF is depends on particle properties and particle surface conditions. However, in all correlation, physical properties of particles are dropped, so new correlation that include physical properties of particles such that roughness, thermal conductivity, density and thermal expansion coefficient is needed for better prediction.

Table 4 Assessment Results of DHF Correlations

| Correlation | Error | *S-S* | *S-M* | *S-L* | *D-S* | *D-M* | *D-L* | *S-VS* | *S-MS* | *D-VS* | *D-MS* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sowa et al. | S.D. | 0.5487 | 0.2244 | 0.0480 | 0.4050 | **0.1796** | **0.0302** | 0.7689 | **0.4235** | 0.3756 | 0.4163 |
| | RMS | 0.5611 | 0.4548 | 0.6000 | 0.4076 | **0.2410** | **0.3511** | 0.7791 | **0.4692** | 0.4018 | 0.4164 |
| Dhir-Catton (a) | S.D. | 0.7731 | 4.5088 | 47.430 | 0.9412 | 3.5674 | 1.7179 | 0.6336 | 0.7485 | 0.7813 | 0.9611 |
| | RMS | 0.7850 | 6.9270 | 72.149 | 1.0200 | 7.1335 | 35.971 | 0.7240 | 0.8086 | 0.7813 | 1.1435 |
| Dhir-Catton (b) | S.D. | 15.123 | 1.6804 | 0.6239 | 36.445 | 7.5876 | 1.5650 | 26.004 | 5.8518 | 41.050 | 33.843 |
| | RMS | 17.271 | 2.9233 | 2.0057 | 57.672 | 14.626 | 7.2330 | 31.749 | 7.6333 | 64.478 | 53.785 |
| Hardee-Nilson | S.D. | 1.1911 | 8.6511 | 109.37 | 1.3745 | 2.0111 | 1.1195 | 0.9288 | 1.2546 | 0.6853 | 1.5212 |
| | RMS | 1.2392 | 12.520 | 151.39 | 1.4508 | 4.7692 | 23.093 | 0.9288 | 1.3362 | 0.7184 | 1.7455 |
| Ostensen | S.D. | 0.5249 | 0.1902 | 0.0220 | **0.3791** | 0.1630 | 0.0274 | 0.7357 | 0.4016 | 0.3749 | 0.3792 |
| | RMS | 0.5513 | 0.4716 | 0.6161 | **0.3803** | 0.2812 | 0.4120 | 0.7396 | 0.4752 | 0.3783 | 0.3870 |
| Shires-Stevens | S.D. | 0.6516 | 4.3250 | 53.215 | 0.6641 | 0.7834 | 0.3109 | 0.5388 | 0.6884 | 0.3549 | 0.7619 |
| | RMS | 0.7014 | 5.5493 | 68.344 | 0.7711 | 1.0567 | 5.5639 | 0.6338 | 0.7271 | 0.7201 | 0.8039 |
| Lipinski | S.D. | **0.5109** | **0.3237** | **0.1047** | 0.3449 | 0.1893 | 0.0698 | **0.5136** | 0.5098 | 0.2038 | 0.3642 |
| | RMS | **0.5151** | **0.3807** | **0.1095** | 0.4145 | 0.4553 | 0.5035 | **0.5375** | 0.5109 | 0.4663 | 0.3837 |
| Jones et al. | S.D. | 0.3318 | 2.2933 | 28.759 | 0.3608 | 0.4544 | 0.2376 | 0.2540 | 0.3522 | 0.1761 | 0.4094 |
| | RMS | 0.7335 | 2.7077 | 38.109 | 0.7269 | 0.4906 | 4.1146 | 0.7785 | 0.7180 | 0.8053 | 0.6791 |
| Dhir-Barleon | S.D. | 0.5077 | 0.1584 | 0.0238 | 0.3656 | 0.1517 | 0.0244 | 0.7146 | 0.3808 | 0.3949 | **0.3463** |
| | RMS | 0.5539 | 0.4935 | 0.6326 | 0.3806 | 0.3381 | 0.4769 | 0.7155 | 0.4912 | 0.3961 | **0.3772** |
| Theofanous-Saito | S.D. | 0.4858 | 0.1987 | 0.0425 | 0.3585 | 0.1590 | 0.0268 | 0.6808 | 0.3750 | **0.3325** | 0.3686 |
| | RMS | 0.5327 | 0.5055 | 0.6456 | 0.3660 | 0.3021 | 0.4252 | 0.6808 | 0.4761 | **0.3327** | 0.3884 |
| Henry-Fauske | S.D. | 1.4231 | 0.4200 | 0.0735 | 1.0981 | 0.3870 | 0.0643 | 1.9953 | 1.0616 | 1.2932 | 0.9820 |
| | RMS | 1.7956 | 0.5814 | 0.1985 | 1.7572 | 0.9193 | 0.3878 | 2.7166 | 1.3501 | 1.9867 | 1.6237 |
| **Notes** | **Data** | **89** | **37** | **7** | **52** | **14** | **3** | **23** | **66** | **19** | **33** |

Table 5 Assessment Results of Over-all Region

| Correlation | Mean Error | S.D. | RMS Error |
|---|---|---|---|
| Sowa et al. | -0.1493 | 0.4623 | 0.4858 |
| Dhir-Catton (a) | 3.9704 | 13.6492 | 14.2149 |
| Dhir-Catton (b) | 16.6573 | 26.8896 | 31.6309 |
| Hardee-Nilson | 6.1980 | 27.1911 | 27.8885 |
| Ostensen | -0.2045 | 0.4356 | 0.4813 |
| Shires-Stevens | 2.0393 | 12.2834 | 12.4516 |
| **Lipinski** | **-0.0164** | **0.4520** | **0.4523** |
| Jones et al. | 0.7534 | 6.9180 | 6.9589 |
| Dhir-Barleon | -0.2603 | 0.4161 | 0.4908 |
| Theofanous-Saito | -0.2468 | 0.4093 | 0.4780 |
| Henry-Fauske | 0.9663 | 1.1811 | 1.5260 |

## 4. Conclusions and Recommendations

Following conclusions can be drawn from this study:

a) Sowa et al., Ostensen, Lipinski, Dhir-Barleon and Theofanous-Saito correlations show relatively good prediction results over all regions. Among them, the Lipinski correlation is the best correlation. That shows generally good prediction in overall region and shows the least error for some specific regions. Because the data with the particle diameter above 0.5mm are dominant, four of the best correlations are based on flooding correlations, excepts Lipinski correlation.

b) The best correlations for medium particle region (1mm to 5mm) are Lipinski correlation (shallow bed) and Sowa et al. (deep bed) correlation. In severe accident, it is expected that the mean particle diameter is varied between 1mm to 5mm and bed thickness exceeds 100mm. So, Sowa et al. correlation is good for severe accident analysis with particle bed formation.

c) If steam explosion occurs, particle diameter is less than 1mm. In that case Lipinski (for shallow bed) or Theofanous-Saito (for deep bed) correlations are good for prediction. If we can expected there will be a deep bed in severe accident, Theofanous-Saito correlation is good for prediction.

d) In shallow beds there is a flooding dominant particle diameter range, but in deep beds it is not certain.

Through this study, following items are recommended;

a) For small particles, especially for shallow beds, there is relatively large error. The least RMS error in this region is greater than 0.5 (50%), so there is strong need for new correlation with enhanced prediction capability.
b) Because DHF is affected by particle properties and surface conditions, there is strong need for new correlation considering particle properties and surface conditions.
c) In corium quenching experiments [3,4], it was observed that the mass averaged mean particle diameter is varied between 1mm and 5mm, so more experiments on 1mm - 5mm particles are required for severe accident analysis. In severe accidents, it is expected that a particle bed in which particle diameter is varied with bed depth may be formed, therefore experiments with mixed particles are required.

## References

1. Blose, R.E. et al., Core-Concrete Interactions with Overlying Water Pools, NUREG/CR-5907, SAND92-1563, 1993.
2. Lipinski, R.J., A Model for Boiling and Dryout in Particle Beds, NUREG/CR-2646, SAND82-0765, 1982.
3. Magalllon, D., Hohmann, H., High Pressure Melt Quenching Test in FARO, NUREG/CP-0127, 1-13, 1994.
4. Mitchel, D.E., Evans, N.A., Steam Explosion Experiments at Intermediate Scale: FITSB Seris, NUREG/CR-3983, 1986.
5. Ostensen, R.W., Lipinski, R.J., A Particle Bed Dryout Model Based on Flooding, Nucl. Sci. Eng., 79, 110-140, 1981
6. Hardee, H.C., Nilson, R.H., Natural Convection in Porous Media with Heat Generation, Nucl. Sci. Eng., 63, 119-132, 1977.
7. Lipinski, R.J., A Particle Bed Dryout Model with Upward and Downward Boiling, Trans. Amer. Nucl. Soc., 35, 358-360, 1980.
8. Fox, H.W. et al., Wetting Properties of Organic Liquids on High Energy Surfaces, J. Phys. Chem., 59, 1097, 1955.