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Jet Impingement Width Calculation for Flat Plate

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Abstract

The flow behavior of the direct vessel injection (DVI) system is important in the analysis of a loss of coolant accident (LOCA) in the Korean Next Generation Reactor (KNGR). Particularly, the flow regime in the downcomer demonstrates thermal-hydraulic characteristics which still defy full understanding. One of the unknown characteristics is the flow velocity profile. The flow behavior during injection is related to the steam path and the amount of bypass of the emergency core cooling (ECC) water. One can obtain the information in an analytical, numerical, or empirical way. First, the analytical method turns out to be only limited in solving the problem at hand because the available equations are not enough to account for all the unknown parameters relevant to the phenomena. In addition, the mathematical and physical methods do not necessarily yield the correct flow pattern. To overcome the limit of this analytical method, a simple experiment was conducted. Two flat acryl plates were used, and the conductance method was used to measure the flow width and thickness. The principle of measurement is that the resistance changes when the sensor reaches the fluid film. Results of the measurements are easily understandable. The outer boundary of and the center of the fluid flow are thick. Also, faster the injection velocity, the larger the flow width. It is remarkable that the velocities at the same spot are nearly identical regardless of the injection velocity. It is considered that, independently of the injected velocities, the spreading effect and the viscosity effect equalize the vertical velocity downstream.

1. Introduction

One of the important features in the KNGR is the DVI system. For this ECC system, however, the flow and temperature patterns during a LOCA have not yet been fully investigated. Also, the experimental and analytical studies on the thermal hydraulic behavior were not complete enough to allow for detailed design. If the behavior of the injected flow in the downcomer during a LOCA is predicted correctly, the reflood capability of the DVI system should be acceptable to protect against the core uncovery. To investigate the behavior of flow, it is necessary to understand the injected flow motion on a vertical wall. This paper presents results from a simplistic jet impingement experiment and analysis.

2. First-Principle Calculation

2.1 Assumptions

To perform this study, several assumptions were made as follows.

1. Neglect the effect of fluid viscosity and wall friction.
2. The area of flow injected into the DVI line is equal to that of flow spreading after striking the wall.
3. The flow thickness spreading to x-direction(horizontal) is the same
4. The injected flow is vertical to the wall
5. The wall is flat
6. The DVI line is internally full of water
7. Steady, incompressible flow

2.2 Procedure

It is assumed that the simple flow regime is combined with the parabola: sketched in [Fig.1].

$$x = v_p \cos\theta \cdot t_1 \tag{1}$$

$$y = v_p \sin\theta \cdot t_1 - \frac{1}{2} \cdot g \cdot t_1^2 \tag{2}$$

where (x, y) is the parabolic point.

The velocity is zero at time t_1, because the flow direction changes. So

$$t_1 = \frac{v_p \sin\theta}{g} \tag{3}$$

$$x = \frac{v_p^2 \sin 2\theta}{2g} \tag{4}$$

$$y = \frac{v_p^2}{2g}\left(\frac{1 - \cos 2\theta}{2}\right) \tag{5}$$

$$\sin^2 2\theta + \cos^2 2\theta = 1 \tag{6}$$

Plug Eqs.(4) and (5) into Eq.(6), then the ellipse equation is obtained.

$$\frac{x^2}{4} + \left(y - \frac{v_p^2}{4g}\right)^2 = \frac{v_p^2}{16g^2} \tag{7}$$

Eq. (7) is the trajectory of the parabola. If the flow boundary consists of many parabolas, assume that the parabola at $\theta = 45^\circ$ is the outermost boundary.

$$y = -\frac{2g}{v_p^2}\left(x - \frac{v_p^2}{2g}\right)^2 + \frac{v_p^2}{2g} \tag{8}$$

2.3 Application 1

We now proceed to calculate the flow width and thickness for the conditions: h = 2.1 m, v_p = 2.5 m/s, D = 0.2 m. Using Eq. (8), the half-width w' is calculated to be

$$w' = 1.2 \text{ m.}$$

To solve for the flow thickness using this mathematical method, the continuity equation is needed.

$$A \cdot v_p = 2 \cdot w \cdot d \cdot v_y \qquad (9)$$

To determine v_y , t_2 has to be calculated.

$$y = \frac{v_p}{\sqrt{2}} \cdot t_2 - \frac{1}{2} \cdot g \cdot t_2^2$$

$$t_2 = 0.86 \text{ sec}$$

$$v_y = -4.89 \quad m/.s$$

Substitute t_2 and v_y into Eq.(10), then find

$$d = 7.8 \text{ mm}$$

2.4 Application 2

We now calculate the flow width and thickness for the conditions: h = 0.5 m, v_p = 1.5 m/s, D : 0.025 m . By the same token we find that

$$w' = 0.38 \text{ m}$$

$$t_2 = 0.45 \text{ sec}$$

$$v_y = -3.35 \; m/.s$$

$$d = 0.5 \text{ mm}$$

3. Proof-of-Principle Test

The DVI jet impingement tests were conducted for the flat plate utilizing the conductance method, which uses the water conductance principle. When the sensor reaches the flow film, the resistance reduces. According to the distance between the sensor and the flow film, the resistance changes rapidly. In this experiment, the major parameter is the flow width, the flow film thickness and the average vertical velocity. Because of difficulty of measuring the average vertical velocity, we only measured the flow width and the film thickness. The average vertical velocity was calculated approximately using the continuity equation.

The test procedure was as follows.

1. After making two acryl flat plate structures, the injection nozzle was attached to the acryl structure, as schematically shown in Figs. 2 and 3.
2. To make local points, the holes were drilled at intervals of 4 cm horizontal, 8 cm vertical.

3. The distance-measure sensor with a good conductance is placed at each hole.
4. The thickness can be measured by the resistance changes.

4. Discussion of Results

The analytical calculation results for the DVI jet impingement are summarized in Table 1. As the viscosity is not considered, the water only flows vertically by the gravity force. To more appropriately calculate the flow behavior, a fluid mechanics model including the viscosity has to be used. For the fluid mechanics method, the mass and the momentum equations are available. On the other hand, the unknown parameters include the vertical velocity, flow width, and flow thickness. If another equation is included, the particle and bulk concept will be used simultaneously. But using the particle and bulk concept is an analytical paradox in that the particle concept for flow is independent of the bulk concept for flow.

For the DVI jet impingement, tests were conducted to check on the computational result. In the experiment, the flow distribution shows that the centerline and flow edges thicken, as well as the upper film. As the injected velocity increases, the upper film thickens and the lower film thins as shown in Tables 2 to 4.

The width of the real flow boundary is illustrated in Fig. 4. The accurate value of the flow boundary is summarized in Table 5. The flow width increases downstream. As the velocity increases, so does the flow width.

As two parameters (the flow width, and thickness) are known, the flow velocity can be calculated by the continuity equation. The results are shown in Tables 6 to 10. Note that velocities are essentially the same at the same height independently of the initial injection velocities. This result indicates that the velocity of DVI during a LOCA need not be very fast to ensure penetration. In fact, a high velocity will bring about the increase in the amount of bypass. A proper velocity of laminar flow without overlapped water jet coming from the adjacent DVI lines will decrease the potential for core uncovery.

5. Conclusion

The DVI system functions as the ECCS in the KNGR design. A hydraulic test for the downcomer was conducted. The experimental results demonstrated the injected water flows along the downcomer, and the flow width, thickness, the vertical velocity. The flow width is proportional to the injected velocity, and the vertical velocities at lower points are virtually identical. The flow velocity from the DVI injection line has adirect bearing upon the ECC bypass, because the flow width and thickness will interfere with the steam path from the core to the break.

References

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Table 1. Application results for the calculation method

	Application 1	Application 2
DVI line diameter	250 mm	30 mm
Injected velocity	2.5 m/s	1.5 m/s
Height	2.1	0.5
Average velocity in h	4.89 m/s	3.35
Flow thickness	7.8 mm	0.5 mm
Flow width	2400 mm	760 mm

Table 2. The flow thickness for v=0.553352 m/s

velocity = 0.553352 m/s **unit** (mm)

							중심선							
A-1 4	A-2	A-3	A-4	A-5	A-6	A-7	A-8	A-9	A-10	A-11	A-12	A-13	A-14	A-15
B-1	B-2	B-3	B-4	B-5	B-6 0.97	B-7 0.47	B-8 2.73	B-9 0.61	B-10 1.03	B-11	B-12	B-13	B-14	B-15
C-1	C-2	C-3	C-4	C-5	C-6 0.34	C-7	C-8 1.19	C-9	C-10 0.56	C-11	C-12	C-13	C-14	C-15
D-1	D-2	D-3	D-4	D-5	D-6 0.42	D-7	D-8 1.02	D-9	D-10 0.47	D-11	D-12	D-13	D-14	D-15
E-1	E-2	E-3	E-4	E-5	E-6 0.66	E-7	E-8 1.08	E-9	E-10 0.52	E-11	E-12	E-13	E-14	E-15
F-1	F-2	F-3	F-4	F-5 0.91	F-6	F-7	F-8 1.07	F-9	F-10	F-11 0.77	F-12	F-13	F-14	F-15

Table 3. The flow thickness for v=1.106704 m/s

velocity = 1.106704 m/s

							중심선							
A-1	A-2	A-3	A-4	A-5	A-6 2.22	A-7 1.59	A-8	A-9 1.37	A-10 1.96	A-11	A-12	A-13	A-14	A-15
B-1	B-2	B-3	B-4 2.17	B-5	B-6 0.61	B-7	B-8 1.32	B-9	B-10 0.46	B-11	B-12 1.94	B-13	B-14	B-15
C-1	C-2	C-3	C-4 1.66	C-5	C-6 0.47	C-7	C-8 0.69	C-9	C-10 0.65	C-11	C-12 1.45	C-13	C-14	C-15
D-1	D-2	D-3	D-4 1.36	D-5	D-6 0.96	D-7	D-8 0.55	D-9	D-10 0.61	D-11	D-12 1.11	D-13	D-14	D-15
E-1	E-2	E-3 1.08	E-4	E-5	E-6 0.6	E-7	E-8 0.51	E-9	E-10 0.67	E-11	E-12	E-13 0.82	E-14	E-15
F-1	F-2	F-3 0.8	F-4	F-5 0.86	F-6	F-7	F-8 0.71	F-9	F-10	F-11 0.69	F-12	F-13 0.72	F-14	F-15

Table 4. The flow thickness for v=1.660056 m/s

velocitv = 1.660056 m/s

							중심선							
A-1	A-2	A-3	A-4	A-5 1.34	A-6 0.94	A-7 0.92	A-8	A-9 1.04	A-10 0.75	A-11 1.39	A-12	A-13	A-14	A-15
B-1	B-2 1.99	B-3	B-4	B-5 0.63	B-6	B-7	B-8 0.85	B-9	B-10	B-11 0.75	B-12	B-13	B-14 1.83	B-15
C-1 1.93	C-2	C-3	C-4	C-5 0.6	C-6	C-7	C-8 0.42	C-9	C-10	C-11 0.65	C-12	C-13	C-14	C-15 2.05
D-1 1.54	D-2	D-3	D-4	D-5 0.61	D-6	D-7	D-8 0.63	D-9	D-10	D-11 0.55	D-12	D-13	D-14	D-15 1.78
E-1 1	E-2	E-3	E-4	E-5 0.6	E-6	E-7	E-8 0.64	E-9	E-10	E-11 0.57	E-12	E-13	E-14	E-15 1.05
F-1 0.92	F-2	F-3	F-4	F-5 0.66	F-6	F-7	F-8 0.6	F-9	F-10	F-11 0.58	F-12	F-13	F-14	F-15 0.77

Table 5. The flow width

0.553352 m/s (unit : cm)

x	y
-12.5	0
-12.5	8
-12.3	16
-12	24
-11.4	32
-10.4	40
-8.6	48
-2.8	56
0	57
3.5	56
8.6	48
10.8	40
12.3	32
13.2	24
13.7	16
13.9	8
13.9	0

center : 52 cm
center radius :1.4cm

1.106704 m/s

x	y
-31.5	0
-30.9	8
-29.7	16
-27.8	24
-25.3	32
-23.3	40
-19.4	48
-14	56
0	63.2
13	56
18.1	48
21.9	40
24.6	32
26.5	24
28.4	16
29.1	8
30	0

center : 55 cm
centerradius : 1.3 cm

1.660056 m/s

x	y
-40.8	0
-39.8	8
-38.1	16
-35.9	24
-32.4	32
-29.8	40
-26.5	48
-21.5	56
-14.1	64
0	68.7
13	64
20.4	56
24.6	48
28	40
31.2	32
34.6	24
36.8	16
37.7	8
38.95	0

center : 55.8 cm
center radius : 1.2 cm

Table 6. The average thickness at line B (8 cm below the injection point)

Velocity(m/s)	Flow width(mm)	Average thickness(mm)	Average velocity(m/s)
0.553352	237	1.16(interpolated)	1.0
1.106704	499	1.3	0.84
1.660056	636	1.21	1.06

Table 7. The average thickness at line C (16 cm below the injection point)

Velocity(m/s)	Flow width(mm)	Average thickness(mm)	Average velocity(m/s)
0.553352	252	0.8(interpolated)	1.35
1.106704	543	0.984	1.017
1.660056	705	1.13	0.9

Table 8. The average thickness at line D (24 cm below the injection point)

Velocity(m/s)	Flow width(mm)	Average thickness(mm)	Average velocity(m/s)
0.553352	260	0.748(interpolated)	1.4
1.106704	581	0.918	1.02
1.660056	749(interpolated)	1.02	1.07

Table 9. The average thickness at Line E (32 cm below the injection point)

Velocity(m/s)	Flow width(mm)	Average thickness(mm)	Average velocity(m/s)
0.553352	264	0.798(interpolated)	1.29
1.106704	600	0.781	1.16
1.660056	775(interpolated)	0.772	1.13

Table 10. The average thickness at Line F (40 cm below the injection point)

Velocity(m/s)	Flow width(mm)	Average thickness(mm)	Average velocity(m/s)
0.553352	264	0.791(interpolated)	1.3
1.106704	615	0.756	1.17
1.660056	796.5(interpolated)	0.706	1.45

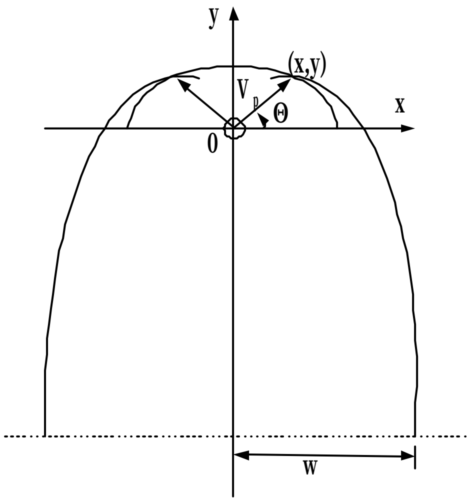

Fig 1. The flow pattern – parabola

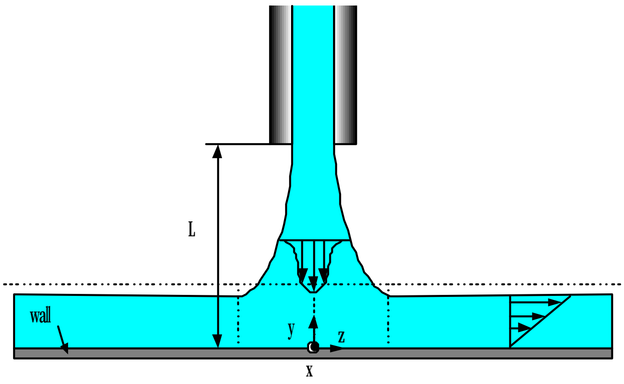

Fig 2. Injection pattern (plan view)

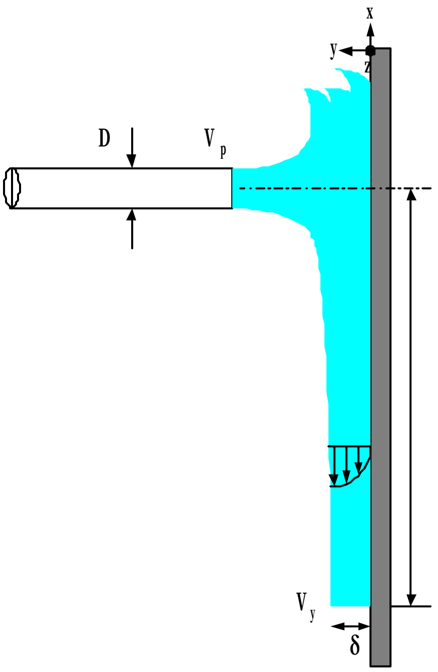

Fig 3. Injection pattern (side view)

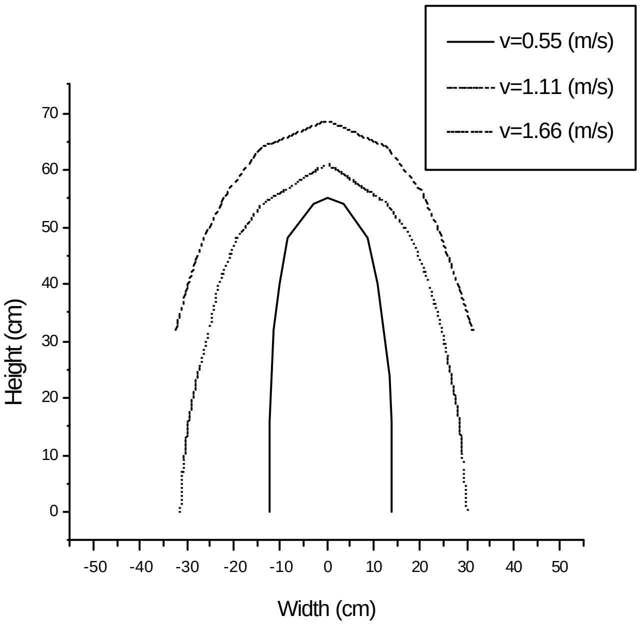

Fig 4. Measured flow boundary

Nomenclature

v_p : injected velocity in the DVI line

$\mathbf{v}_y$: y-directional velocity at h

$\mathbf{v}_{avg,x}$: x-directional average velocity

$\mathbf{v}_{avg,z}$: z-directional average velocity

t_1 : the response time until the flow direction changes

t_2 : response time until the water flows at h

θ : spreading angle of flow ($0° \leq \theta \leq 180°$)

D : DVI line diameter

h : distance between DVI line and measurement point

w' : half-width

δ : flow thickness