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Investigation of horizontal cold water discharge initial dilutions at various temperature differences using duckbill valve

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ABSTRACT

Thermal pollution, that is a temperature change in natural water body, can have adverse effects on the organisms in the aquatic environment as river, lake, or ocean. A common cause of thermal pollution is the use of water as a cooling and heating system by power plants, liquefied natural gas (LNG) regasification terminals, and industrial manufacturers. Cold water discharges into a receiving water body, which are mainly originated from LNG regasification terminals from open cycle heating units, are a kind of thermal effluent. Disposal of cold water with an environmentally protective way can be applied as a dilution method using marine outfall systems. In order to obtain a better dilution in a marine outfall, there is a multiport diffuser at the end of the pipeline. Experimentally performed single port analysis of an outfall is a method of initial dilution investigation for performance determination of designed system. Because of the fact that cold water discharge is denser than receiving ambient water in the marine environment, it is a negatively buoyant dense jet. In this study, horizontally discharged cold water jet initial dilutions at various temperatures were experimentally investigated in a laboratory model using duckbill valve discharge port. Three discharge temperature differences were used as $\Delta T_0 = -3$, -5, and -7°C in the laboratory model for determination of the initial dilutions, S, in the cold water jet centerline. Densimetric Froude numbers (F) were calculated as 446.03, 358.43, and 321.76 for the selected temperature differences, respectively. This laboratory model study was also aimed at obtaining some experimental coefficients, such as impingement point distance, as design criteria for horizontally discharged cold water outfalls using duckbill valves.

Keywords: Thermal pollution; Cold water discharge; Negatively buoyant jet; Dilution; Marine outfall; Duckbill valve

1. Introduction

Thermal pollution has come to mean the detrimental effects of temperature changes in a natural water body, caused by the discharge of cooling and heating water system from industrial facilities as power plants and liquefied natural gas (LNG) regasification terminals [1–3]. Due to the biological sensitivity of many aquatic organisms to water temperature, temperature changes may have multiple impacts on aquatic ecosystems [4–7]. Aquatic organisms are highly dependent on specific thermal conditions in aquatic environments;

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water temperatures above or below optimal thermal regimes can cause stress or even death [8,9].

Many researchers have focused on developing effective methods for heat water discharges in today. However, cold water is also discharged into the receiving environment from some industrial processes such as LNG receiving terminals [10,11]. Cold water discharge has some undesirable effects on aquatic organisms. Especially, cold-blooded aquatic organisms; fish for example, virtually all aspects of their reproduction, feeding, growth, and survival are highly sensitive to temperature due to hypothermia [12–16]. Cold water discharges also include some antifouling chemicals, chlorine for instance [13,17]. In addition, the cold water density is higher than the receiving water. Due to the high density of cold water jets, especially at higher temperatures than 4°C, it is a kind of negatively buoyant jets. Thus, cold water is one of the important sources of negatively buoyant wastewater jets [18].

Cold water jets have tendency to sink to the bottom of receiving ambient [19,20]. Because of this sinking tendency of cold water jet, it is difficult to ensure well mixing and dilution in a limited water column height. In order to increase dense jet centerline trajectory, nozzle inclination is a commonly used method. However, there are some new offshore located LNG receiving terminals. They need to discharge cold water near to sea surface at an elevated position. In order to dilute their cold water in a limited water depth, a submerged horizontally installed cold water discharge could be selected instead of inclined nozzle on the sea bottom.

Most of marine outfall diffusers have circular ports for discharging their effluents. However, circular ports could be problematic about sea water intrusion and some clogging problems because of low jet velocities at ports. In order to increase discharged jet velocity at port, duckbill valves could be widely used on outfall diffusers [21]. Duckbill check valve hydraulics details were studied by Lee et al. [22,23]. No matter how most of studies on duckbill valve applications on outfall diffusers, Roberts and Duer [24] were studied on cold water injection in water storage tanks. They were found use of duckbill ensures better cold water mixing conditions comparing circular port.

In this study, horizontally discharged cold water jet initial dilutions at various temperatures were experimentally investigated in a laboratory model using duckbill valve discharge port. Three discharge temperature differences were used in the laboratory model for determination of the initial dilutions, S, in the cold water jet centerline. Densimetric Froude numbers (F), experimental coefficients related to jet geometry, effluent dilution, and its position were calculated at the selected temperature differences for design criteria of horizontally discharged cold water outfalls using duckbill valves.

2. Materials and method

2.1. Analysis

The condition of nozzle is shown Fig. 1. A horizontally placed nozzle discharges through a round nozzle of diameter d at a velocity u. Analyses of negatively buoyant flow regime have been reported by Pincince and List [25], Roberts and Toms [26], and others. On the other hand, this type of discharge was characterized by these authors as its kinematic fluxes of volume Q, momentum M, and buoyancy B as Eq. (1),

$$Q = \frac{\pi}{4} d^2 u; \quad M = uQ = \frac{\pi}{4} d^2 u^2; \; B = \frac{\pi}{4} d^2 u g'_0 \qquad (1)$$

where $g'_0 = g(\rho_0 - \rho_a)/\rho_0$ initial value of modified gravitational acceleration; g = gravitational acceleration; ρ_0 = effluent density, and ρ_a = ambient density. From these fluxes, two length scales can be formed as Eq. (2)

$$l_M = \frac{M^{3/4}}{B^{1/2}} \quad \text{and } l_Q = \frac{Q}{M^{1/2}} \qquad (2)$$

These important length scales have been discussed by several scientists, including Wright [27]. l_Q is a measure of the distance over which the volume flux of entrained ambient fluid becomes approximately equal to the initial volume flux, Q; for distances from the nozzle much greater than l_Q, the initial volume flux becomes dynamically unimportant. For a positively buoyant jet, l_M is a measure of the distance over which the buoyancy generates momentum approximately equal to the initial momentum flux, M; for distances from the nozzle much greater than l_M, the effect of initial momentum becomes negligible. Nevertheless, for the current case of a negatively buoyant jet, the momentum flux will always be an important parameter because of the fact that the vertical component of momentum and buoyancy are not in the same direction.

When fully turbulent flow condition is assumed, in order to ensure, the effects of molecular viscosity or Reynolds number are negligible, any dependent variable will be a function of B, M, and Q. The terminal rise height y_t, for example, can be shown as Eq. (3)

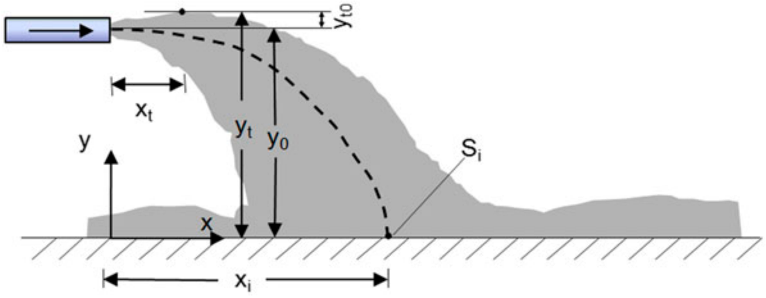

Fig. 1. Definition sketch for horizontally discharged cold water jet.

$$y_t = f(B, M, Q) \tag{3}$$

which, following dimensional analysis and expressed in terms of length scales, becomes Eq. (4)

$$\frac{y_t}{l_M} = f\left(\frac{l_M}{l_Q}\right) \tag{4}$$

For dilution, related expression on the lower boundary ($y = 0$) can be formed by assuming that the Boussinesq assumption holds, i.e. density differences are much smaller than absolute densities at any point in the flow field. The local modified gravitational acceleration can be obtained as the dependent variable as Eq. (5),

$$g' = g\left(\frac{\rho_0 - \rho_a}{\rho_0}\right) = f(Q, M, B, x) \tag{5}$$

where ρ = local density. Following a dimensional analysis, (5) becomes Eq. (6),

$$\frac{B^{3/2}}{g'M^{5/4}} = f\left(\frac{l_M}{l_Q}, \frac{x}{l_M}\right) \tag{6}$$

The dilution $S = g'_0/g'$, so (6) can be described as Eq. (7),

$$S\frac{l_Q}{l_M} = f\left(\frac{l_M}{l_Q}, \frac{x}{l_M}\right) \tag{7}$$

where S refers to a time-averaged value.

For $l_M >> 1$, the source volume flux dynamic effect becomes negligible, and Q or l_Q dropout as parameters. Eqs. (4) and (7) become as Eqs. (8) and (9).

$$\frac{y_t}{l_M} = c; \quad S\frac{l_Q}{l_M} = f\left(\frac{x}{l_M}\right) \tag{8,9}$$

where c is an experimental constant.

These results are often expressed in terms of the nozzle diameter and jet densimetric Froude number, $F = u/\sqrt{g'_0 d}$, instead of length scales, as reported by Roberts et al. [19]. The modified expressions are as Eq. (10),

$$l_M = \left(\frac{\pi}{4}\right)^{1/4} \mathrm{d}F \quad \text{and } l_Q = \left(\frac{\pi}{4}\right)^{1/2} d \tag{10}$$

Eqs. (8) and (9) can be written as Eqs. (11) and (12),

$$\frac{y_t}{\mathrm{d}F} = c_1; \quad \frac{S}{F} = f\left(\frac{x}{\mathrm{d}F}\right) \tag{11,12}$$

where c_1 is an experimental constant. The effects of volume flux on dilution and rise height become negligible for $F \geq 20$, as experimentally reported by Roberts and Toms [26]. In order to keep same approach to make analysis of dense jets, $F \geq 20$ would be a norm and source volume flux will be assumed to be negligible. The dilution at the impact point S_i can be obtained from (12). All normalized jet parameters were summarized in Table 1 as $C_1, \ldots, C_6$ experimental coefficients (constants).

The Froude number F was used in its modified form designed for cold water discharge (for dense jet) as given in Equations as Eqs. (13) and (14) reported by Bayat et al. [18],

$$F = \frac{u}{\sqrt{g.d.|\Delta\rho/\rho_0|}} \tag{13}$$

$$\Delta\rho = \rho_0 - \rho_a \tag{14}$$

where $\Delta\rho$: difference of water densities.

Using Equation as Eq. (15), local dilutions S were obtained.

Table 1
Experimental coefficients

Quantity	Equation	Coefficient
Terminal rise height from bottom	$y_t/\mathrm{d}F =$	C_1
Terminal rise height from nozzle center	$y_{t0}/\mathrm{d}F =$	C_2
Terminal rise height horizontal distance from nozzle	$x_t/\mathrm{d}F =$	C_3
Location of impact point	$x_i/\mathrm{d}F =$	C_4
Impact point dilution	$S_i/F =$	C_5
Dilution at terminal rise height from bottom	$S_t/F =$	C_6

$$S = \Delta T_0/\Delta T_{\max} \tag{15}$$

where $\Delta T_{\max}$: the maximum temperature difference in any of the cross sections of the jet;

($\Delta T_0 = T_0 - T_a$), where T_a is temperature of ambient water and T_0 is discharged water temperature.

2.2. Experimental setup

In this study, it is aimed to obtain initial dilution values in cold water discharge using a laboratory model at three different discharge temperatures with horizontal duckbill mounted port. Nozzle diameter was $d = 0.5$ cm and a duckbill valve with a pipe conjunction having 0.7 cm inner diameter was mounted in front of circular port. Experimental studies were performed by 0.48 L/min flow rate, Q. Under this flow rate condition, duckbill valve opening area was captured from a digital camera. Cross-sectional area of flow was calculated from digital image and an imaginer circular port diameter was calculated as $d = 0.2311$ cm. Port velocity was also calculated as $u = 1.90691$ m/s. The receiving water environment was stagnant and homogeneous. Water depth of receiving ambient over the nozzle center, $h = 50$ cm. Three discharge temperature differences were used as $\Delta T_0 = -3$°C (22.3–25.3), −5°C (20.3–25.3), and −7°C (18.3–25.3) in the laboratory model for determination of the initial dilutions, S, in the cold water jet centerline. Densimetric Froude numbers (F) for three temperature differences (−3, −5, and −7°C) were calculated as 446.03, 358.43, and 321.76, respectively. Totally nine experiments were conducted. The experiments summary is given in Table 2.

The cold water discharge was carried out by pumping the cooled water in 0.1 g/L concentration, containing Rhodamine B as tracer, into the experiment tank filled with fresh water. As the first stage, the cold water jet was allowed to move freely until a stable regime is obtained while the course is being photographed. The motion is determined to cold water jet outer surface characteristics, such as dense jet terminal raise height, y_t, etc. Afterwards, a series of temperature sensors connected to a mobile mechanism are immersed into the jet to determine temperature distribution in the jet cross-section and the jet centerline coordinates via a scanning method. Temperature measurements were performed by drawing the sensors from the most distant point near the source. In these measurements, seven PT100 temperature sensors with 4 mm diameter and 3 cm length were placed within 10 cm distance to each other were used with a Lufft Opus 200 device. Cooling process was prepared by PolyScience digital water bath, where initial density measurements were made by an Anton Paar DMA 4500 device. The dimensions of the experiment tank are 76.5 cm × 196 cm × 119.5 cm (width × length × height). The top surface of the tank is open while the other surfaces are made of transparent Plexiglas. Discharge port was placed horizontally according to an adjustable tank floor. Discharge flow rate was set by McMillan S-112 digital flow-meter and flow was maintained by Cole-Parmer Masterflex pump. Jet centerline coordinates and dilution values obtained by immersed temperature probes into the jet bodies.

3. Results and discussion

3.1. Jet geometry

All of the horizontally cold water at the three temperature differences discharged into stagnant and homogenous, receiving water and very high such densimetric Froude numbers, 446.03, 358.43, and 321.76 were performed. All of the discharged cold waters such as density jets were formed momentum jets, and then gradually changed their trajectories onto the bottom as negatively buoyant jets. Momentum dominated cold water jets after the impingement point jumped and then formed a density current. Horizontally discharged cold water jets with $\Delta T_0 = -3$, −5, and −7°C, respectively, instantaneous images were given in Figs. 2–4.

Table 2
Summary of experiments

Experiment number	T_0 (℃)	T_a (℃)	ρ_o (kg/m^3)	ρ_a (kg/m^3)	d (mm)	y_0 (mm)	ν ($\times10^{-6}$) (m^2/s)	u (m/s)	R	F	y_0/dF	L_M (mm)	y_0/L_M
CJ ΔT_0= −3 (1)	22.3	25.3	998.068	997.258	2.311	110	0.951	1.9069	4630.9	446.0352	0.106	970.38	0.113
CJ ΔT_0 = −3 (2)	22.3	25.3	998.068	997.258	2.311	110	0.951	1.9069	4630.9	446.0352	0.106	970.38	0.113
CJ ΔT_0 = −3 (3)	22.3	25.3	998.068	997.258	2.311	110	0.951	1.9069	4630.9	446.0352	0.106	970.38	0.113
CJ ΔT_0 = −5 (1)	20.3	25.3	998.503	997.258	2.311	110	0.997	1.9069	4416.5	358.4367	0.132	779.80	0.141
CJ ΔT_0 = −5 (2)	20.3	25.3	998.503	997.258	2.311	110	0.997	1.9069	4416.5	358.4367	0.132	779.80	0.141
CJ ΔT_0 = −5 (3)	20.3	25.3	998.503	997.258	2.311	110	0.997	1.9069	4416.5	358.4367	0.132	779.80	0.141
CJ ΔT_0 = −7 (1)	18.3	25.3	998.803	997.258	2.311	110	1.048	1.9069	4205.0	321.7606	0.147	700.01	0.157
CJ ΔT_0 = −7 (2)	18.3	25.3	998.803	997.258	2.311	110	1.048	1.9069	4205.0	321.7606	0.147	700.01	0.157
CJ ΔT_0 = −7 (3)	18.3	25.3	998.803	997.258	2.311	110	1.048	1.9069	4205.0	321.7606	0.147	700.01	0.157

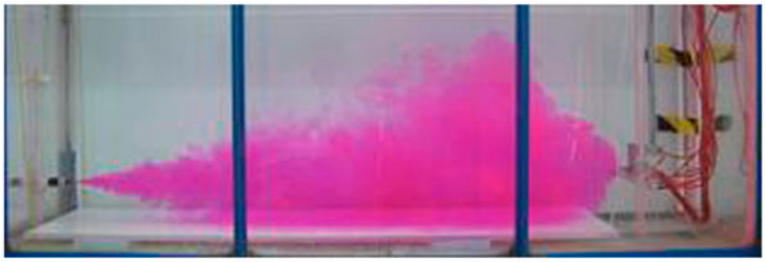

Fig. 2. Cold water jet instantaneous image for ΔT_0 = −3℃.

Fig. 3. Cold water jet instantaneous image for ΔT_0 = −5℃.

Fig. 4. Cold water jet instantaneous image for ΔT_0 = −7℃.

Terminal rise height to the bottom, y_t, for the discharge temperature differences, cold water main jet body values were measured from image analysis of Figs. 2–4 and their animated movies. The analysis of the outer surface images of cold water jets in the same scale, due to the increased temperature difference, were shown increasing negative buoyancy in fixed momentum conditions. However, despite the increase in discharge temperature differences, horizontal distances between cold water jet impingement point to the discharge source, x_i, were decreased. The impingement points of $\Delta T_0 = -3$℃ experiments could not be detected at the determined measurement points in the experimental tank. Average normalized cold water jet impingement point distances, $x_i/\mathrm{d}F$, were closely measured as 1.387 and 1.366 for $\Delta T_0 = -5$ and -7℃.

3.2. Jet centerline trajectory

Fig. 5 is given normalized centerline trajectories of cold water jets for $\Delta T_0 = -3$, -5, and -7℃. Before impingement points, freely discharged part of main cold water jet bodies had precipitation movement as studies of Katano et al. [28]. This movement of cold water jet bodies continues until pre-impingement point to the bottom. Cold water jet bodies formed a density current after the impingement point. Due to cold water jets behave as density jets, their behaviors of jet centerline axis before and after impingement points have been found similar to Nemlioglu [29], Bayat et al. [18], Nemlioglu and Sezgin [12] (for $\Delta T_0 = -5$℃ and using duckbill valve) and Nemlioglu and Sezgin [2] (for $\Delta T_0 = -5$℃ and using circular valve) cold water jets studies and Shao and Law [30] brine discharge studies.

3.3. Dilution

Maximum temperature differences ($\Delta T_{\max}$) of horizontally discharged cold water jets in jet centerline were given in Fig. 6 for $\Delta T_0 = -3$, -5, and -7℃. According to Fig. 6, the maximum temperature differences in jet centerline were very closely measured and were very quickly decreased for three temperature differences at the horizontal distance from the nozzle.

Fig. 7 was shown normalized initial dilutions, S/F, for $\Delta T_0 = -3$, -5, and -7℃, depending on the horizontal normalized distance. Also normalized initial dilutions of Nemlioglu and Sezgin [12], and Nemlioglu and Sezgin [2] studies were compared in Fig. 7. Normalized initial dilutions of cold water jets were determined as very close each other until impingement points for $\Delta T_0 = -3$, -5, and -7℃. After the impingement points, the values of S/F were scattered in Fig. 7. S/F values for $\Delta T_0 = -3$, -5, and -7℃ were found similar to Nemlioglu and Sezgin [12] studies, but lower than Nemlioglu and Sezgin [2] studies.

The comparisons of initial dilutions, S, (non-normalized and depending on the horizontal distance) with Nemlioglu and Sezgin [12] and Nemlioglu and Sezgin [2] studies were given in Fig. 8 for $\Delta T_0 = -3$, -5, and -7℃.

It was shown in Fig. 8, initial dilutions of cold water changed each other depend on increasing horizontal distance from the nozzle for $\Delta T_0 = -3$, -5, and -7℃. Initial dilutions of cold water discharge using duckbill nozzle were found higher than circular nozzle discharge as expected. In addition, S values of $\Delta T_0 = -5$℃ in this study were found similar to Nemlioglu and Sezgin [12] studies.

The recommended experimental coefficients, $C_1, \ldots, C_6$, were given in Table 3. Averages of the

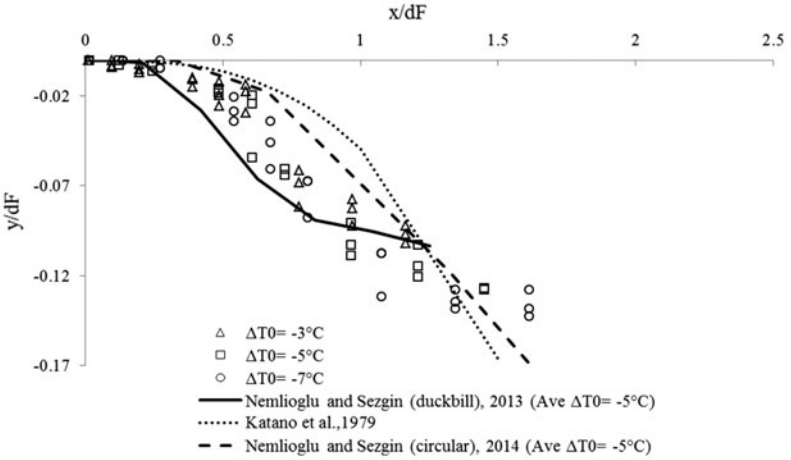

Fig. 5. Cold water jet centerline trajectory comparison for $\Delta T_0 = -3$, -5 and -7℃.

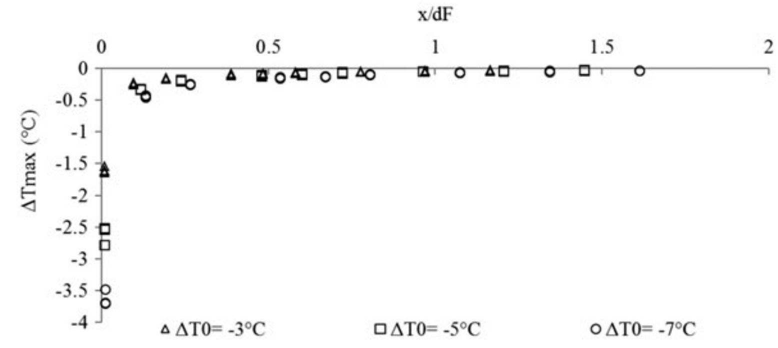

Fig. 6. Temperature differences of cold water in the jet centerlines for $\Delta T_0 = -3$, -5, and -7˚C.

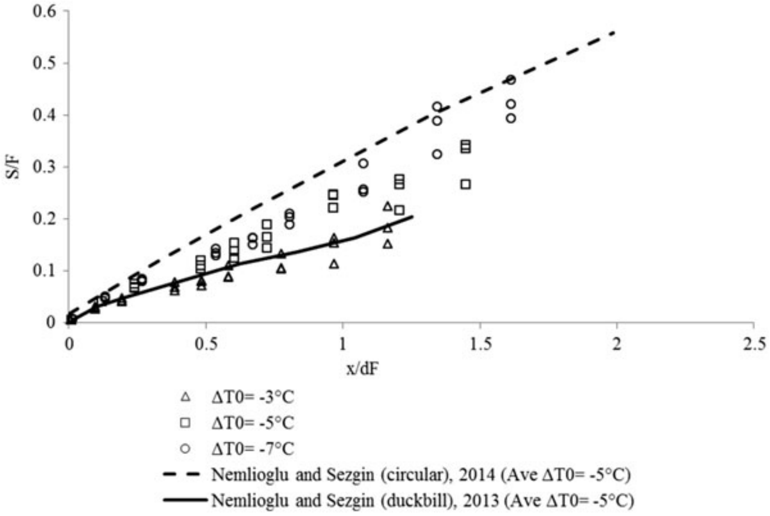

Fig. 7. Comparison of normalized initial dilution cold water in the jet centerline for $\Delta T_0 = -3$, -5, and -7˚C.

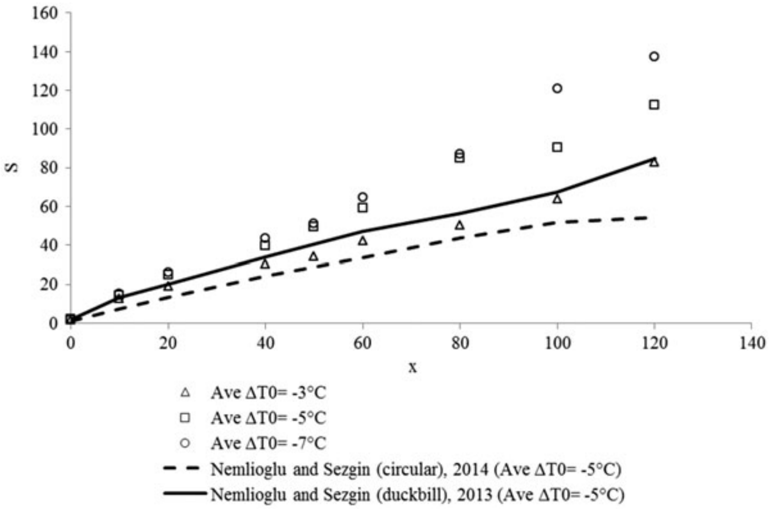

Fig. 8. Comparison of initial dilution cold water in the jet centerline for $\Delta T_0 = -3$, -5, and -7˚C.

Table 3
Summary of experimental coefficients

Experiment number	C_1	C_2	C_3	C_4	C_5	C_6
CJ $\Delta T_0 = -3$ (1)	0.374	0.267	1.042	N.D	N.D	0.185
CJ $\Delta T_0 = -3$ (2)	0.374	0.267	1.011	N.D	N.D	0.158
CJ $\Delta T_0 = -3$ (3)	0.316	0.209	0.989	N.D	N.D	0.117
Average CJ $\Delta T_0 = -3$	0.354	0.247	1.014	N.D	N.D	0.153
CJ $\Delta T_0 = -5$ (1)	0.414	0.281	0.966	1.388	0.253	0.219
CJ $\Delta T_0 = -5$ (2)	0.422	0.289	1.034	1.448	0.340	0.251
CJ $\Delta T_0 = -5$ (3)	0.329	0.196	1.050	1.327	0.304	0.256
Average CJ $\Delta T_0 = -5$	0.388	0.255	1.016	1.387	0.299	0.242
CJ $\Delta T_0 = -7$ (1)	0.361	0.213	1.012	1.412	0.348	0.243
CJ $\Delta T_0 = -7$ (2)	0.338	0.190	1.087	1.344	0.387	0.251
CJ $\Delta T_0 = -7$ (3)	0.356	0.208	1.031	1.344	0.414	0.290
Average CJ $\Delta T_0 = -7$	0.351	0.203	1.043	1.366	0.383	0.261

Note: N.D: Not Detected

coefficients for each ΔT_0 values were calculated in the same table.

According to Table 3, average of $C_1 = y_t/\mathrm{d}F$, $C_2 = y_{t0}/\mathrm{d}F$, $C_3 = x_t/\mathrm{d}F$, and $C_4 = x_i/\mathrm{d}F$ (not detected for $\Delta T_0 = -3$°C) values were found very closely for $\Delta T_0 = -3$, -5, and -7°C. Also it is shown from Table 3, average $C_5 = S_i/\mathrm{d}F$ value for $\Delta T_0 = -7$°C was found higher than $\Delta T_0 = -5$°C value. Because of Reynolds number of discharged cold water for $\Delta T_0 = -7$°C lower than discharged cold water for $\Delta T_0 = -5$°C, turbulence of discharged cold water for $\Delta T_0 = -7$°C was lower in the ambient water. Hence, normalized initial dilution (or C_5 value) of discharged cold water for $\Delta T_0 = -7$°C was found higher than $\Delta T_0 = -5$°C at the impingement points. In addition, $C_6 = S_t/F$ values as it was expected were found 0.153, 0.242, and 0.261 for $\Delta T_0 = -3$, -5, and -7°C, respectively, in the same reasons of $C_5 = S_i/\mathrm{d}F$. Average results of C_1, C_2, C_3, C_4, and C_5 coefficients in this study were found similar to Nemlioglu and Sezgin [12] (for $\Delta T_0 = -5$°C and using duckbill valve), 2013 studies. Average results of C_1, C_2, C_3, C_4, and C_5 coefficients were found 0.404, 0.289, 1.018, 1.251, and 0.204 by Nemlioglu and Sezgin [12], respectively.

4. Conclusion

The effects of source temperature differences on thermal initial dilution of horizontal cold water discharge using duckbill valve into stagnant and homogenous receiving water were investigated in this study. The cold water discharges behaved as negatively buoyant jets, and they formed density currents after the bottom impingement points. The normalized cold water jets impingement points distances, $x_i/\mathrm{d}F$, were measured closely each other in the range of the selected source temperature differences. The normalized centerline axis trajectories of cold water jets were very close to each other and they were determined similar to freely falling cold water jet centerline trajectory model by Katano et al. [27], until impingement points.

The normalized initial dilution (S/F) results of cold water discharge using the duckbill valve and circular valve are not different each other were determined. High Froude numbers were effective for using duckbill valve in these results. Initial dilution results (not normalized, S) of cold water discharge using duckbill nozzle were found higher than circular nozzle discharge.

Consequently, the use of duckbill valve could be an advantageous method for shallow receiving water, and suspended effluents desired conditions.

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