Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.20247

65 (2017) 136–141
February

Initial dilution comparison of wastewater marine outfall diffusers with sharp-edged ports in thick diffuser pipe wall and duckbill check valves

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Received 1 May 2016; Accepted 2 October 2016

ABSTRACT

Domestic wastewater marine outfall diffusers can be set up with sharp-edged circular ports. These simple and cylindrical ports opened on diffuser pipe wall have two main types: (1) sharp-edged port in thin-walled diffuser pipe (TN) and sharp-edged port in thick-walled diffuser pipe (TK). Because of less minor head loss, TK has 20% higher flow rate capacity than TN in same hydraulic head condition. No matter how TKs are better than TN type, TK type ports are still open-ended holes in very dynamic seawater ambient. TK ports suffer from clogging risk because of sediment transportation and seawater intrusion into diffuser pipe during less wastewater flow rate periods. In order to protect TK ports, an elastomer and one-way flow providing "duckbill" check valve (DBV) with same nominal size can be mounted on circular ports. This rehabilitation method could specifically be applied on domestic wastewater discharging marine outfalls after start of their operational period. However, additional DBV part could change original hydraulic and initial dilution conditions, due to increased minor head losses and jet velocities. In this study, TK to DBV nozzle type conversion effects on initial dilution were discussed. Q = 0.5 m^3/s design flow rate, t = 30 years lifespan, H = 20–50 m port depths, and ρ_a = 1,015–1,035 kg/m^3 receiving water densities, 12 different diffusers with d = 150 mm diameter sized TK circular ports were designed and converted to 150 mm regular (not wide type) DBV nozzles. All hydraulic parameters and initial dilutions of before and after DBV usage were recalculated from literature data for line source in this study. Initial dilution comparisons between original and DBV converted conditions as ΔS (%) were varied from –10.77 to 6.53 for at the end of lifespan, t = 30 years with 33% positive values. For the first days of life span, t = 0 year, ΔS (%) were varied from –9.10 to 10.94 range with 50% positive values.

Keywords: Duckbill check valve; Initial dilution; Marine outfall rehabilitation; Domestic wastewater discharge; Sharp-edged port; Multiport diffuser

1. Introduction

Domestic wastewaters originated from coastal cities can be conventionally discharged into marine environment via marine outfalls with multiport diffusers based on environmental concerns. Multiport diffusers of marine outfalls can be constructed with a number of circular holes (port) directly opened on sides of diffuser pipes. These ports could maintain the shortest passage for wastewater jet during its inside to outside route of transportation. Directly opened circular ports are called as "sharp-edged ports", if they are not rounded (other than bell-mouthed port) at inside of diffuser pipe. According to diffuser pipe wall thickness, t_w, and port diameter, d, there are two main types of sharp-edged ports: thin-walled sharp-edged port (TN) has $t_w/d < 0.5$, and thick-walled sharp-edged port (TK) has $t_w/d > 1$ [1]. TK has 20% higher flow rate than TN. Because of higher discharge performance of TK, in many applications throughout the

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world, wall thickness of diffuser pipes were increased at port sections by attaching small pipes, which have same size with port etc. instead of selecting thick-walled pipes. In this way, many of thin-walled outfall multiport diffusers were economically converted to TK involving systems, making them highly favorable.

In order to maintain a continuous wastewater flow, diffusers are designed for completely full cases during their operational lives. Nevertheless, because of very changeable nature of domestic wastewater, flow rate is highly difficult to set a fully flowing regime in a multiport diffuser with open-ended TK holes. Particularly in the first operational years of an outfall with TK involving diffuser, actual flow rate will be considerably lower than its design value. As a consequence, saline intrusion into the diffuser is nearly inevitable. Saline intrusion is a carrying movement of sediment, etc. Hence, it could result in undesired conditions caused by blockage risk of diffuser and/or port(s).

Outfall diffusers with open-ended circular ports such as TK type could be protected from saline intrusion by using a one-way flow-maintaining part, elastomer nozzle "duckbill" check valve (DBV). DBV nozzles could be easily applied on open-ended ports [2] as mounted section of a diffuser.

Duer [3] reported that after DBV application onto diffusers, their initial dilutions could reach higher levels by increased wastewater jet velocity at port, u. Singular port flow and dilution characteristics were experimentally investigated in lab scale by some researchers, such as Sezgin [4], and Nemlioglu and Sezgin [5]. They indicated horizontal cold water jet initial dilution increase for circular port changed as DBV nozzles. Roberts and Duer [6] also stated improvement of cold water initial dilution in closed freshwater tanks based on their experimental studies. Lee et al. [7] conducted an experimental study about discharge hydraulics of some of the commonly used conventional DBVs (without wide bill) in practice, and reported empirical hydraulic equations for these selected nozzles. Many of researchers stated high initial dilution performance of single-port DBV discharges. On the contrary of these studies, in a study of Duer and Salas [8], it was reported that initial dilution level of a circular port could be decreased if it is converted to a DBV nozzle at deeper positions than H = 20 m port depths. Same idea was also confirmed by Nemlioglu [9] with calculations on the same source hydraulic head conditions for change from TN port to DBV nozzle type outfall multiport diffusers. A simple equation (Eq. (1)) was also developed by Nemlioglu [10] for circular TN port dilution, $S_{c\text{–TN}}$ to DBV nozzle converted dilution, S_{DBV}, regarding receiving ambient density, ρ_a, as given below:

$$S_{\text{DBV}} = (0.0012\ \rho_a - 0.5207)\ S_{c\text{–TN}} - 0.4722\ \rho_a + 507.68 \quad (1)$$

Initial dilution estimations were also indicated very similar tendency for TK port to DBV nozzle conversion in multiport diffuser conditions by Yilmaz [11].

Open port applications of DBV nozzles give very successful results about initial dilution increase comparing original port performance of open-ended conditions. However, for multiport applications of circular port to DBV nozzle converted conditions, there are a couple of studies mentioning port depth is a very important parameter for initial dilution increase or decrease [8–11]. In this study, initial dilution effects of DBV conversion of TK circular ports are summarized for multiport diffuser condition. There is also a comparison DBV conversion of TN circular ports in Nemlioglu's study [10].

2. Materials and methods

In this study, initial dilution estimation changes were investigated in such cases as before and after conversion of horizontal circular sharp-edged ports in thick pipe wall (TK) to duckbill valve (DBV) in domestic wastewater outfall multiport diffusers. 12 outfall diffusers were designed with TK ports for same flow rate, project lifespan, wastewater density, various receiving water densities, and port depths which were described below. Then, all calculations of open-ended circular TK ports were repeated after this conversion. Design upstream hydraulic heads were kept constant before and after the conversion for all diffusers. Hydraulic parameters were calculated for all cases, followed by estimation and comparison of initial dilution levels for both designed and first operational years. All calculation and estimation details were given below.

Selected design parameters of this study are lifespan, t = 30 years; design flow rate, Q = 0.5 m^3/s; port depths, H = 20, 30, 40, and 50 m; effluent density, ρ_0 = 1,000 kg/m^3; and receiving water densities, ρ_a = 1,015, 1,025, and 1,035 kg/m^3. Twelve separate diffusers with d = 150 mm port diameter were designed. The original design port shape was sharp-edged type and opened at thick-walled pipe circular port (TK). Internal hydraulic calculations of diffusers with TKs were performed according to Rawn et al. [12] suggested procedure as summarized in Eq. (2) for flow rate at n indexed (port numbers start from downstream) port, q_n:

$$q_n = C_{Dn} a_n \sqrt{2gE_n} = C_{Dn} \frac{\pi d_n^2}{4} \sqrt{2gE_n} = u_n a_n \quad (2)$$

where C_{Dn} is the discharge coefficient; a_n is the port area; g is the gravitational acceleration (adopted as 9.81 m/s^2); E_n is the hydraulic head at port; d_n is the port diameter; and u_n is the velocity at port. C_{Dn} values for TKs were adopted as 1.2 multiplied values of TN case according to Miller's study [1].

Total energy at the last port E_N (upstream section) value was calculated for per diffuser, as well. Slope of diffusers, which were located on the seabed, was assumed as horizontal. Darcy–Weisbach friction factor, f = 0.02 (assumed constant), port spacing between subsequent ports, l = 5 m, and main pipeline length without diffuser section, L_{main} = 1,500 m were selected. According to chosen design flow rate, served population was defined as N_{30} = 172,800 persons for t = 30 years lifespan. For the first service year, t = 0 year, served population and flow rate were also defined as N_0 = 71,192 persons and Q_0 = 0.206 m^3/s, respectively. Velocity values in diffuser pipe, v, were limited to 0.6–0.9 m/s range, which were adopted from Grace's study [13].

Estimated values of initial dilutions of designed diffusers with circular TK ports, S_c (dilution, $S = c_0/c$ where c_0 is source pollutant concentration, and c is diluted local pollutant concentration), were calculated from Fan and Brooks experimental results for line source [14].

After designing of TK ports with multiport diffusers, all ports of diffusers were converted to conventional

150 mm DBV nozzles. DBV nozzles were not wide type and as they were described in Lee et al. [7] study. Eqs. (3)–(5) were reorganized from Lee et al. [7]:

$$u_n = \sqrt{2g\left(\frac{E_n}{1.196}\right)^{\left(\frac{1}{0.961}\right)}} \quad (3)$$

$$a_{jn} = 0.729\left(\frac{u_n^2}{2gE_n}\right)^{0.593} a_n \quad (4)$$

$$q_n = u_n a_n = u_n \pi \frac{d_n^2}{4} = u_{jn} a_{jn} \quad (5)$$

In DBV case, u_n and a_n parameters were at internal part of DBV nozzle as before for described TK port, where u_{jn} is the jet velocity, and a_{jn} is the effective port area, respectively.

Total head values of all diffusers were kept same before and after nozzle type conversion. All hydraulic parameters were recalculated in compliance with the experimental study of Lee et al. [7] as well as the dilution estimations (S_{DBV}). Dilution comparisons for the end of project lifespan were obtained from ΔS (%) = 100 × (S_{DBV} – S_c)/S_c. All dilution estimations were compared using S_c base value in their operational year and their E_N total head values. For start of operational process of outfall systems as t = 0 year, all calculations were also performed for Q_0 flow rate. Following a comparison of t = 30 years and circular port condition with same E_N values, total active port number of diffuser values, N, showed difference. Active port number values, N_a, were defined from diffuser hydraulic calculations. Inactive port number values, N_i, were calculated from $N_i = N - N_a$.

3. Results and discussion

Original design parameters of open circular TK ports with diffusers were summarized in Table 1 for the end of lifespan, t = 30 years. After DBV nozzle conversion, two third of dilutions decreased ΔS rates by percentage between –5.16 and –10.77. One third of dilution changes were occurred in the range between 0.96 and 6.53, compared with circular ports. As shown in Table 1, ΔS (%) rates decreased by increasing H and ρ_a values. Maximum incremental difference was calculated as ΔS (%) = 6.53 for H = 20 m, ρ_a = 1,015 kg/m^3, and E_N = 1.16 m in TK 01 case. On the other hand, maximum decremental difference was found as ΔS (%) = –10.77 for H = 50 m, ρ_a = 1,035 kg/m^3, and E_N = 2.61 m in TK 12 case. All wastewater jet velocities at ports were also shown in Table 1. Jet velocities in DBV nozzles were always figured 1.9 times higher than TK ports. These u values were also 1.2 higher than TN ports. These jet velocity differences were encountered owing to 20% higher flow rate performance of TK ports comparing with TN ports. Nevertheless, increased jet velocities were resulted in decreased dilution levels in 67% of investigated cases. In addition, all active port numbers were decreased in diffusers with DBV under same total head conditions of circular TK ports.

N_a values and diffuser lengths were dramatically decreased for all cases after DBV use in diffusers. On the other hand, shown in Fig. 1 are both TK and TN vs. DBV conditions initial dilution comparisons for t = 30 years for all investigated diffusers. In Fig. 1, TN-related part was reproduced from previous TN vs. DBV study, which was performed by Nemlioglu [9]. It is obvious that at the end of the lifespan of systems, t = 30 years, S_c values resulted mostly in higher figures similar to S_{DBV} dilutions for both TK and TN port conditions as seen in Fig. 1. Dilution differences between DBV and circular ports were increased, when dilution values increased for both sharp-edged port types. However, there were two critical dilution levels for $S_{DBV} > S_c$ conditions where S_c values were lower than 125 and 100, for TK and TN port types, respectively.

In Fig. 2, E_N–ΔS (%) relation at the end of lifespan of system was given with respecting receiving water density, ρ_a, and port depth, H values. All curves in Fig. 2 were plotted for H = 20–50 m, from left to right side. As shown in Fig. 2, increasing values of receiving water density were effected

Table 1
Circular TK port and duckbill mounted diffuser characteristics summary for end of lifespan (t = 30 years)

Nozzle type:			Circular TK port				Duckbill check valve					Comparison	
Case No.	ρ_a (kg/m^3)	H (m)	E_N (m)	u (m/s)	N_a	S	E_N (m)	u (m/s)	N_a	N_i	S	ΔS	ΔS (%)
TK 01	1,015	20	1.16	3.37	9	92.60	1.16	6.63	7	2	98.66	6.05	6.53
TK 02	1,015	30	1.31	3.59	8	125.34	1.31	6.99	7	1	127.15	1.81	1.44
TK 03	1,015	40	1.46	3.80	8	161.05	1.46	7.40	6	2	152.73	–8.32	–5.16
TK 04	1,015	50	1.61	4.00	8	192.51	1.61	7.79	6	2	176.48	–16.03	–8.32
TK 05	1,025	20	1.36	3.68	8	98.29	1.36	7.16	6	2	102.02	3.72	3.79
TK 06	1,025	30	1.62	4.01	8	137.72	1.62	7.81	6	2	131.45	–6.26	–4.54
TK 07	1,025	40	1.85	4.32	7	172.56	1.85	8.35	6	1	158.32	–14.24	–8.25
TK 08	1,025	50	2.11	4.61	7	202.69	2.11	8.91	5	2	183.44	–19.25	–9.49
TK 09	1,035	20	1.58	3.96	8	102.76	1.58	7.70	6	2	103.73	0.97	0.94
TK 10	1,035	30	1.91	4.39	7	144.17	1.91	8.49	5	2	134.05	–10.11	–7.01
TK 11	1,035	40	2.27	4.78	6	177.90	2.27	9.23	5	1	161.63	–16.27	–9.14
TK 12	1,035	50	2.61	5.15	6	209.67	2.61	9.92	5	1	187.08	–22.58	–10.77

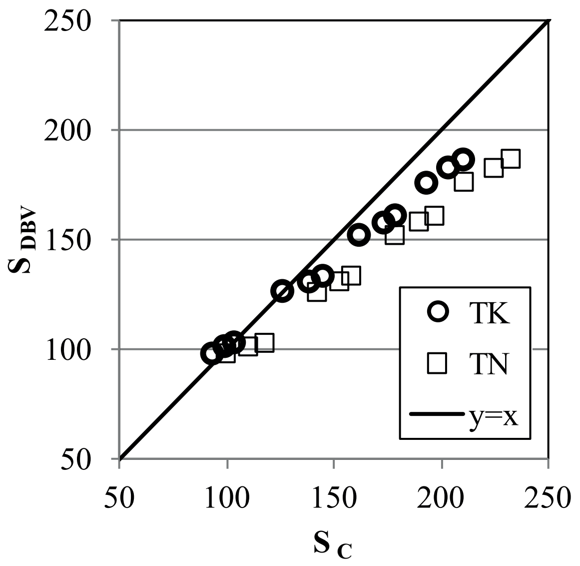

Fig. 1. Initial dilution comparisons of sharp-edged ports as TK and TN types vs. DBV nozzle converted conditions outfalls (TN vs. DBV cases were reproduced from Nemlioglu [9]).

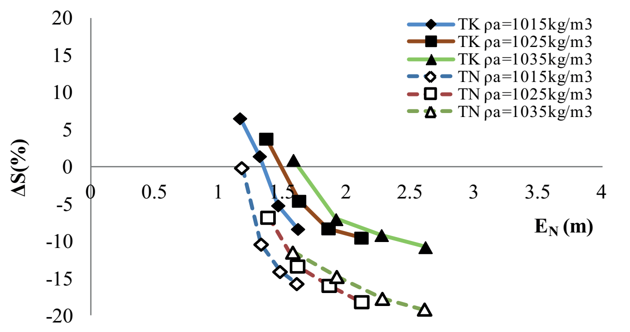

Fig. 2. E_N–ΔS (%) relation for t = 30 years (TN vs. DBV cases were reproduced from Nemlioglu [9]).

E_N values likewise for same flow rate capacity. Increasing port depths also increased E_N values. Under these conditions, minimum and maximum dilution differences were found to be ρ_a = 1,015 kg/m^3 and ρ_a = 1,035 kg/m^3, respectively. In 33% of investigated cases, TK ports had positive ΔS (%) values on the contrary to TN ports case, which were taken from Nemlioglu's study [9].

For the first days of project lifespan, t = 0 year, Table 2 shows the comparison of dilutions, jet velocities, and active port numbers. Because of lower flow rates, active port numbers for t = 0 year were all lower than t = 30 years condition. S and ΔS (%) values were obtained for lower flow rate of t = 0 year and higher level of E_N values, as result of less head loss of main pipeline with same total energy of whole marine outfall systems. Change in dilutions with DBV in comparison with TK ports ranged from ΔS (%) = –9.10 to 10.94. Increasing H and ρ_a levels decreased ΔS (%) values as seen in Table 2. 50% of these values are in the positive range. Negative ΔS (%) values were observed at high H and ρ_a values. For low ρ_a values, ΔS (%) could be calculated as positive values. After TK to DBV nozzle conversion, 25% of N_a values were constant for t = 0 year with N_i = 0.

Comparison between circular TK and TN ports vs. DBV converted initial dilution was given in Fig. 3 for t = 0 year (TN vs. DBV cases were reproduced from Nemlioglu [9]). Conversions from TK ports to DBV were more effective comparing TN–DBV relations. All H = 20 m DBV dilutions were higher than both TK and TN cases. However, even for H = 30 m conditions, TK to DBV conversions were still more effective, with the only exception of ρ_a = 1,035 kg/m^3 case, which has a ΔS (%) value near or equal to zero, on the contrary to less effective TN to DBV conversions for t = 0 year. 50% of ΔS (%) values for TK were positive in the range of investigated H and ρ_a values. Approximately, S_c = 150 is the critical value for TKs. When S_c > 150 condition was occurred, ΔS (%) values for TK were all turned to negative side. On the other hand, the critical value of S_c was declared as 100 for TN ports by Nemlioglu [9]. Fig. 4 clearly shows that in E_N–ΔS (%) relations for t = 0 year, ΔS (%) values for TK were all higher than TN type. 50% of TK conversions to DBV were

Table 2
Circular TK port and duckbill mounted diffuser characteristics summary for operation start (t = 0 year)

Nozzle type:			Circular TK port				Duckbill check valve					Comparison	
Case No.	ρ_a (kg/m^3)	H (m)	E_N (m)	u (m/s)	N_a	S	E_N (m)	u (m/s)	N_a	N_i	S	ΔS	ΔS (%)
TK 01	1,015	20	1.77	4.17	3	86.54	1.77	8.18	3	0	96.01	9.47	10.94
TK 02	1,015	30	1.85	4.27	3	115.96	1.85	8.34	3	0	121.12	5.16	4.45
TK 03	1,015	40	2.07	4.54	3	142.70	2.07	8.86	2	1	146.59	3.89	2.72
TK 04	1,015	50	2.30	4.80	3	172.33	2.30	9.35	2	1	168.93	–3.39	–1.97
TK 05	1,025	20	1.93	4.38	3	92.13	1.93	8.56	3	0	97.71	5.58	6.06
TK 06	1,025	30	2.31	4.81	3	121.43	2.31	9.37	2	1	126.13	4.70	3.87
TK 07	1,025	40	2.45	4.97	3	159.02	2.45	9.65	2	1	152.75	–6.26	–3.94
TK 08	1,025	50	2.54	5.06	3	193.94	2.54	9.82	2	1	176.27	–17.66	–9.10
TK 09	1,035	20	2.25	4.75	3	95.00	2.25	9.25	2	1	100.23	5.23	5.51
TK 10	1,035	30	2.54	5.06	3	130.29	2.54	9.81	2	1	129.93	–0.35	–0.27
TK 11	1,035	40	2.80	5.30	3	168.27	2.80	10.29	2	1	154.99	–13.28	–7.89
TK 12	1,035	50	3.25	5.74	3	197.47	3.25	11.08	2	1	180.85	–16.61	–8.41

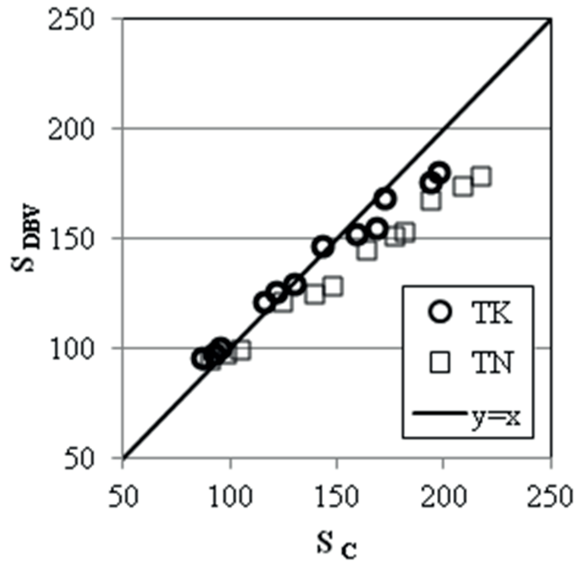

Fig. 3. Dilution comparison circular vs. DBV port used conditions of same diffusers for t = 0 years (TN vs. DBV cases were reproduced from Nemlioglu [9]).

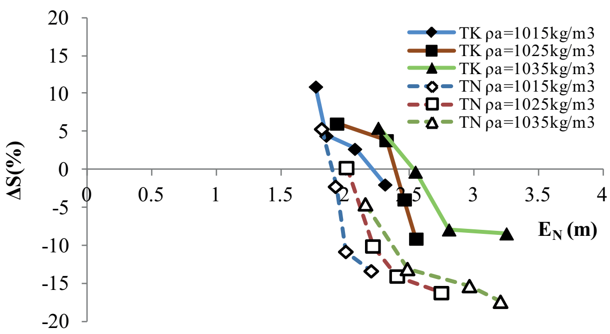

Fig. 4. E_N–ΔS (%) relations for t = 0 years (TN vs. DBV cases were reproduced from Nemlioglu [9]).

positive on the contrary to only two ΔS (%) values of TN's conversions. Both TK and TN conversions to DBV for t = 0 year had higher E_N and ΔS (%) values comparing t = 30 years conditions.

4. Conclusion

In order to decrease contamination levels of domestic wastewater pollutants when discharged into a marine environment, it is a traditional method for coastal cities to dilute wastewater with a high mixing capacity using a multiport diffuser in a marine outfall. Open-ended, sharp-edged circular ports could widely be used in such marine outfall diffusers. Sharp-edged circular ports in a thick pipe wall (TK) could be preferred because of higher flow rate capacity compared with same type ports in thin pipe wall (TN). No matter how high performance TK ports have, they are still open-ended holes on the seabed, and they need protection from seawater intrusion into the diffuser and sediment removal with high jet velocities during operational seasons and periods with low flow rates. DBV type nozzles could maintain one-way flow regime, and both protect the diffuser from seawater intrusion and increase wastewater jet velocity when directly mounted on TK or TN ports. Many of studies mentioned increased dilution successes about regular type of DBVs. However, because of higher levels minor head loss of DBVs, dilution levels could be lower compared with circular ports on H = 20 m or higher depths as mentioned by Duer and Salas [8]. Same condition was also confirmed in detail by Nemlioglu [9] for TN ports. TK, the more common type of sharp-edged port, was investigated from the standpoint for their DBV type nozzle conversion in multiport conditions with originally circular d = 150 mm port diameter TK ports. Regular DBV nozzles were attached with such assumptions as lifespan, t = 30 years, and project start t = 0 year, for design flow rate, Q = 0.5 m^3/s; port depths, H = 20, 30, 40, and 50 m; effluent density, ρ_0 = 1,000 kg/m^3; and receiving water densities, ρ_a = 1,015, 1,025, and 1,035 kg/m^3 for 12 separate diffusers. This study shows that for t = 30 years, TK to DBV nozzle conversion negatively changed initial dilution levels as two third of investigated typical cases to be between ΔS (%) = –5.16 and –10.77. Case changes in positive range occurred in the range between 0.96 and 6.53. Wastewater jet velocities in DBV nozzles were found always 1.9 times higher than TK ports.

For the first days of project lifespan, t = 0 year, ΔS (%) of TK to DBV nozzle change values ranged from –9.10 to 10.94. Half of ΔS (%) values were positive. Negative ΔS (%) values were obtained at higher H and ρ_a values in the investigated ranges of this study. On the contrary to t = 30 years condition, H = 30 m depth still gave positive ΔS (%) values in most cases for t = 0 year. This conclusion suggests TK to DBV conversion should be useful for early stages of operational processes of this kind of outfall diffusers. This case also emphasizes that DBV conversions should be more efficient in TK ports than TNs due to more effective nature of TK with regard to jet flow rate to TN port comparison.

This study shows that TK to DBV conversion could decrease one third of initial dilutions for t = 30 years, and half of such of t = 0 year cases in typical conditions. However, initial dilution decrease rates were lower than all TN to DBV conversion cases. When initial dilutions are considered, TK to DBV conversion is more effective than TN to DBV conversion. For seawater intrusion protection, DBV use should still be suggested if overall conditions were evaluated no matter how port shape conversions could cause decrease on initial dilution values in some cases, as a rehabilitation method for existing marine outfalls with TK ports.

Acknowledgment

This work was supported by Research Fund of the Istanbul University (project No.: BEK-2016-20874).

Symbols

ΔS	—	Dilution difference between circular and DBV nozzle
ΔS (%)	—	Dilution comparison percentage between circular and DBV nozzle

ρ_0	—	Effluent density
ρ_a	—	Receiving water density
a_{jn}	—	Effective port area of DBV nozzle
a_n	—	Port area
c	—	Diluted local pollutant concentration
c_0	—	Source pollutant concentration
C_{Dn}	—	Discharge coefficient
d and d_n	—	Port diameter
DBV	—	Duckbill check valve
E_n	—	Hydraulic head at port
E_N	—	Total energy at the last port
f	—	Darcy–Weisbach friction factor
g	—	Gravitational acceleration
H	—	Port depth
l	—	Distance between subsequent ports
L_{main}	—	Main pipeline length to diffuser
N	—	Total port number of original diffuser for $t = 30$ years
N_0	—	Served population for $t = 0$ year
N_{30}	—	Served population for $t = 30$ years
N_a	—	Active port number
N_i	—	Inactive port number
Q	—	Flow rate
Q_0	—	Flow rate for $t = 0$ year
q_n	—	Flow rate at n indexed port
S	—	Dilution
$S_{c\text{–TN}}$	—	Dilution of circular TN port
S_c	—	Dilution of circular port
S_{DBV}	—	Dilution of duckbill check valve
t	—	Operational year, lifespan
TK	—	Thick-walled sharp-edged port
TN	—	Thin-walled sharp-edged port
t_w	—	Diffuser pipe wall thickness
u and u_n	—	Jet exit velocity at port
u_{jn}	—	Jet velocity (from DBV nozzle)
v	—	Velocity in diffuser pipe

References

[1] D.S. Miller, Internal Flow: A Guide to Losses in Pipe and Duct Systems, The British Hydromechanics Research Association, Cranfield, Bedford, England, 1971.

[2] P.J.W. Roberts, H.J. Salas, F.M. Reiff, M. Libharer, A. Labbe, J.C. Thomson, Marine Wastewater Outfalls and Treatment Systems, IWA Publishing, London, UK, 2010.

[3] M.J. Duer, Use of Elastomeric "Duckbill" Valves for Long-term Hydraulic and Dilution Efficiency of Marine Diffusers, International Conference on Marine Waste Water Discharges 2000 (MWWD 2000), Genova, Italy, 2000, pp. 483–493.

[4] N. Sezgin, Investigation of horizontal cold water discharge initial dilutions at various temperature differences using duckbill valve, Desal. Wat. Treat., 57 (2016) 2437–2445.

[5] S. Nemlioglu, N. Sezgin, Use of Duckbill Valve on Horizontal Cold Water Discharge Initial Dilution, 6th International Perspective on Water Resources and the Environment Conference (IPWE), Izmir, Turkey, 2013, p. 55.

[6] P.J.W. Roberts, M.J. Duer, Physical Modeling of Mixing in Water Storage Tanks, AWWA Research Foundation, Denver, 2006.

[7] J.H.W. Lee, J. Karandikar, P.R. Horton, Hydraulics of "Duckbill" elastomer check valves, J. Hydraul. Eng., 124 (1998) 394–405.

[8] M.J. Duer, H.J. Salas, Use of "Duckbill" Valves to Maintain Marine Outfall Diffuser Efficiency, Inter-American Association of Sanitary and Environmental Engineering Congress 26 (AIDIS 98), Environmental Management in the 21st century, APIS, Lima, Peru, 1998, pp. 1–8.

[9] S. Nemlioglu, Duckbill elastomer check valve use effects on domestic wastewater discharging marine outfalls initial dilution performance improvement, Desal. Wat. Treat., 57 (2016) 2576–2581.

[10] S. Nemlioglu, Initial dilution Effects of Duckbill Check Valve Use in Domestic Wastewater Marine Outfall Diffusers, 7th Urban Infrastructure Symposium, Trabzon, Turkey, 2015, pp. 357–362 (in Turkish).

[11] S. Yilmaz, An Investigation on Duckbill Check Valve Use Effects on Initial Dilution of Domestic Wastewater Marine Outfalls, MSc Dissertation, Institute of Science, Istanbul University, Istanbul, Turkey, 2015 (in Turkish).

[12] A.M. Rawn, F.R. Bowerman, N.H. Brooks, Diffusers for disposal of sewage in sea water, Trans. ASCE, 126 (1961) 344–388.

[13] R.A. Grace, Marine Outfall Systems Planning, Design and Construction, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1978.

[14] N.H. Brooks, Dispersion in Hydrologic and Coastal Environments, Report No. EPA-660/3-73-010, Office of Research and Monitoring, U.S. Environmental Protection Agency, Washington, D.C., 1973.