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MODEL TESTS ON THE FLOW CHARACTERISTICS OF A CYCLONE GAS SCRUBBER

by

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SUMMARY

As a basis for elucidating the performance of a cyclone gas scrubber, a Perspex model, one-tenth full size, was built. Complete similarity between the laboratory and commercial scales of operation is not possible, and sealing parameters relating to the gas-flow are relaxed. The flow pattern of the gas was traced by the addition of talc, and the performance evaluated by absorbing sulphur dioxide into water from the inlet air at concentrations of order 200 mg m^{-3}. Problems were encountered with the entrainment of droplets, and preventive measures are described.

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INTRODUCTION

The promulgation of the Clean Air Act 1972 has emphasised the need for understanding the "best practical means" of rendering gaseous discharges to the atmosphere as least obnoxious as possible. For example, in the ventilation of dens for superphosphate manufacture, significant quantities of acidic fluorine gases are carried off in the air, which is discharged to atmosphere. The contaminants are corrosive and are potentially injurious to plant life, and thus must be removed from the offgas stream to an acceptable degree. The present standards are that the emitted gas must not contain more than 100 mg F^-/m^3 dry gas measured at 0^oC and 103.15 kPa, from existing installations, and not more than 50 mg F^-/m^3 dry gas from new plant (1). Existing plant may be required to be upgraded to reduce emissions below the limit of 50 mg/m^3 in the future.

Traditionally, packed columns have been used in fertilizer works as offgas scrubbers with water as the scrubbing liquor. Spray towers, venturi scrubbers and wet-cell washers are also employed (2). Packed columns, although simple and relatively cheap devices, are limited in scrubbing efficiency and require considerable quantities of water for effective operation. A tower packed with 50 x 50 mm Raschig rings, for instance, might need about 60 kg s^{-1} of water for unit cross-sectional area (1 m^2) (3).

Fresh water use can be reduced by liquor recycle, but multistaging is needed if an acceptable overall efficiency is to be obtained owing to the significant vapour pressure of the dissolved acids (HF, H_2SiF_6) at the highest concentrations (4). A two-stage arrangement is shown in Fig. 1.

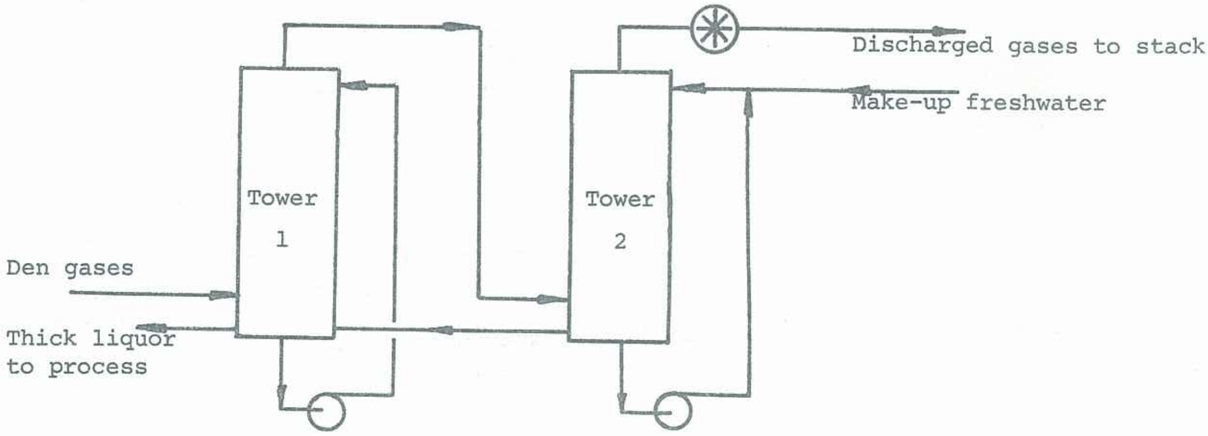


Fig. 1 A two-tower arrangement for the scrubbing of superphosphate-den gases with liquor recycle

In recent years, a local fertilizer works replaced its old packed column with a cyclone-scrubbing system of novel design. To elucidate the behaviour of the twin cyclones, coupled as in Fig. 1, laboratory tests were undertaken on a model of the actual absorber. It was hoped to determine the gas-flow pattern as a basis for understanding the performance of the unit.

SCALING CRITERIA

The inlet gas to each absorber is drawn into the chamber by an induced-draught fan placed in the duct between the final scrubber and the outlet stack. The gas enters tangentially, one-third the way up from the base of the conical bottom of the chamber, and is scrubbed with atomized liquor from six spray-boxes set on a spiral that is considered to match the gas spiral. The liquor is sprayed in flat, fan-shaped jets at right-angles to the direction of the gas motion. The upper section of the cyclonic scrubber is designed to act as a disentrainment device, so that no liquid droplets are carried over into the next stage. The liquor level is controlled at a height just below the gas inlet, and a cruciform vortex-divider is installed to reduce liquid swirl. Facilities exist for recycling liquor, along with fresh make-up water, to each scrubber.

Two main aspects must be considered in scaling such absorption equipment. These are: the process-engineering characteristics of the plant and the physico-chemical absorption. The former is concerned with the fluid dynamics of the two-phase system; the latter with the contacting and the removal of the soluble gaseous constituents. Both aspects are interrelated.

The gas motion is characterised by the Reynolds number, $u_o D_c/\nu$, where u_o is the specific volumetric gas-flow based on the inlet-duct section ($m^3\ m^{-2}\ s^{-1}$), D_c is the chamber diameter (m) and ν is the kinematic viscosity of the gas ($m^2\ s^{-1}$). In the commercial plant, the value of u_oD_c/ν is of order 10^6 so that a model one-tenth scale would require inconveniently large inlet-gas velocities for dynamic similarity.

The liquid sheet issuing from a fan-jet is unstable; sinuous waves are formed which disintegrate into ligaments that themselves break up into droplets (5).

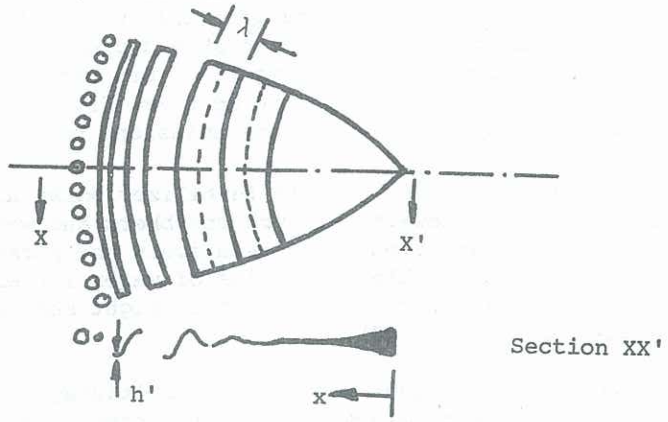


Fig. 2 Successive stages in the idealized break-up of a wavy sheet (5)

This break-up is characterised by the Weber number, $\rho_L U_s h'/2\sigma$, where ρ_L is the liquid density ($kg\ m^{-3}$), U_s is the sheet velocity ($m\ s^{-1}$), h' the break-up thickness of the fan-spray sheet (m), see Fig. 2, and σ is the surface tension ($J\ m^{-2}$). If the liquid/gas ratio is to be held constant, then dynamic similarity for the fan-jet would demand an impossibly large surface tension for the liquid to be atomized.

Similar conclusions are recorded by Hoftyzer and Van Krevelin (6), who note that for absorption in packed columns it is impossible to carry out an operation in the laboratory in such a way that is similar to that in a plant of commercial size. Specifically they note that in the absorption of carbon dioxide in alkaline solutions, the relative absorption is not a common function of lye concentration. It was decided, then, to relax the requirement of gas-motion similarity, but to design the laboratory experiments to simulate as far as possible similar droplet-cloud conditions which are more determinative of the rate of absorption.

NOZZLE DESIGN

The volume-surface mean drop size of the spray issuing from the fan-sheet is given by the expression (7)

$$d_{vs} = 900 \times 10^{-6} \left| \frac{K\sigma}{C_o \Delta P} \right|^{1/3} \frac{\rho_L}{\rho_G}^{1/6} , \quad \rho_G < 2/kg\ m^3 \qquad (1)$$

in which C_o is the orifice-discharge coefficient (~ 0.9), ΔP is the nozzle pressure drop (Pa) and K is a parameter which has dimensions of area (m^2). This parameter, which uniquely describes the sheet geometry, is defined as the product of the sheet thickness h and the corresponding distance from the nozzle x:

$$K = hx \qquad (2)$$

The value of K is also obtainable from the angle subtended by the sheet at the orifice θ, if the edges of the sheet were unconstrained by surface tension and the exit passage within the nozzle: i.e.

$$K = \sin^{-1} (\pi D_o^2/4)/\theta \qquad (3)$$

Injection pressure influences the value of K and for a given orifice size K tends asymptotically to a constant value with increase in pressure. The value is also markedly influenced by viscosity, increasing rapidly as the viscosity rises, but the rate of increase diminishing with injection pressure.

The spraying characteristics of a nozzle from the full-scale plant were determined when spraying water into air. The flow-rate was adjusted to give a similar flow to that on the industrial plant, namely 263 ml s^{-1} per spray. The angle of the spray produced (62^o) agreed with a value interpolated from published data (8) for similarly sized nozzles (4.75 mm).

Pressure, kPa	69	172	(test) 275	345	690
Flow / ml s^{-1}	142	233	263	338	486
Angle, °	50	59	62	65	65

The break-up length for the spray was calculated from the Dombrowski-Hooper correlation (7) for ambient air densities less than 2 kg m^{-3}, which corresponds to $2\pi h/\lambda < 1/4$, where λ is the wavelength of the ripples on the disintegrating sheet. The length so computed is 15.2 mm with a corresponding thickness of 5.3 µm; these values yield $K = 80.8 \times 10^{-8}/m^2$. The mean drop size from equation 1 is 120 µm. This size is of the same order (100 µm) as that recommended by Johnstone and Roberts (9) as a compromise between large interfacial areas (small d_{VS}) for effective contacting and large particle sizes for ready disentrainment of droplets from the gas-stream. Performance data (10) for the Pease-Anthony-type of cyclonic-spray scrubber, in which the sprays are located on a central manifold, indicate that the droplets produced are in the mist range, 50 to 100 µm.

The foregoing considerations led us to assume that the published data (7,8) could be used for the design of the model nozzle. The smallest nozzle, for which data are available (8), is 0.787 mm in diameter. For a spray angle of 62° and the corresponding K value from equation (3), the estimated flow rate through the nozzle would be about 6 ml s^{-1} by interpolating the data of Dombrowski and Johns (11). The length of the spray sheet for this angle would be about 20 mm, and the mean droplet diameter was calculated to be 20 µm from equation (1). This value implied that the ratio of the droplet diameter to that of the chamber was 0.6×10^{-4} for the proposed model, one-tenth full size, whereas the ratio for the commercial plant was 1×10^{-4}. The ratio of the length of the fan-spray sheet to the chamber diameter was also considered to be a valid parameter; at both the laboratory and commercial scales this ratio was approximately 0.08. The actual volumetric liquid/gas ratio was greater in the model chamber at 0.116 compared with a nominal 0.059 in the full-scale plant, but this discrepancy was considered to be of secondary importance, particularly in view of fluctuations in den ventilation.

The nozzle-orifice plate was made from 1.59 mm thick rubber sheeting, the dimensions of the industrial nozzle being scaled down by one-sixth. The front and back faces of the nozzle were made the same (Fig. 3(b)). The orifice plates were placed in a small brass cylinder of the same internal diameter as that of the orifice and secured by p.v.c. tubing which was inserted into the brass tube (Fig. 3(a)). Four such jets were incorporated into each spray assembly so that each flat spray sheet was inclined at 60° to the horizontal towards the incoming gas-stream.

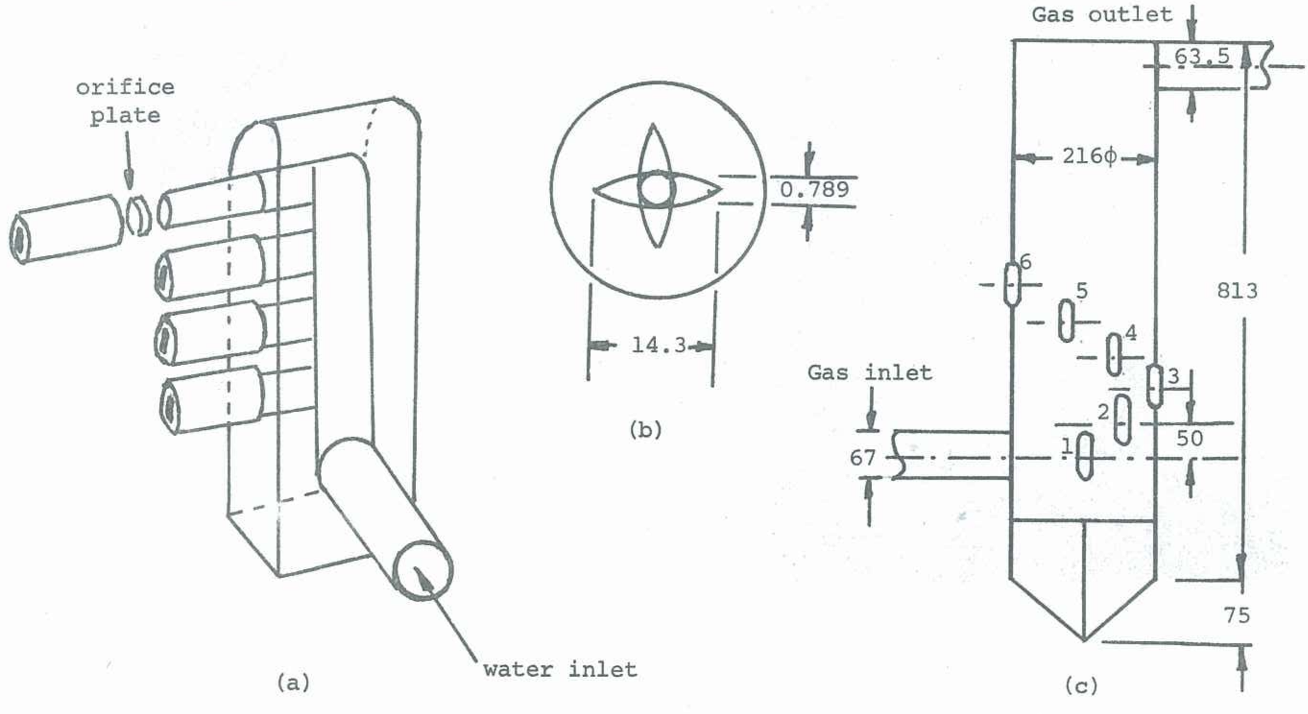


Fig. 3 Model nozzle system. (a) Spray-box assembly. (b) Orifice plate. (c) Location in chamber. All dimensions in mm.

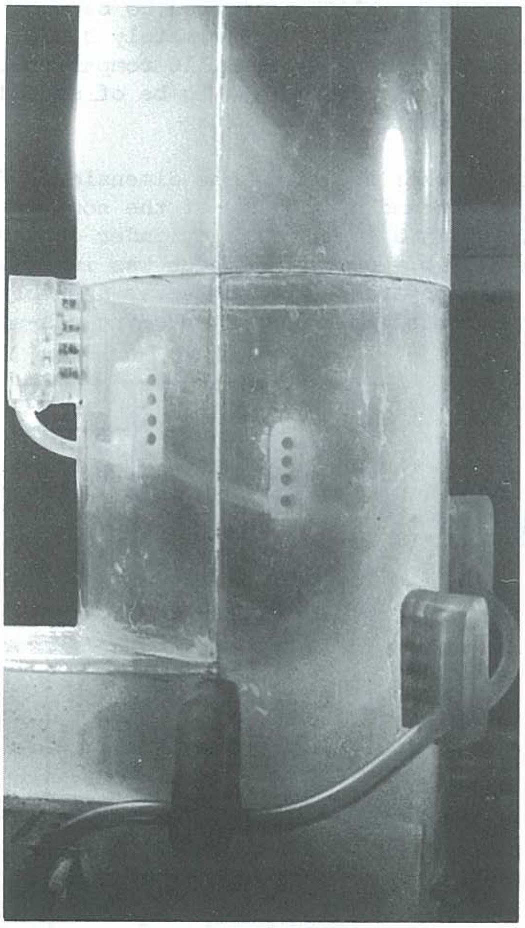
The cylindrical part of the cyclone was fabricated from Perspex (at one-tenth full size), and the spray-box assemblies were fitted around the chamber at similar relative positions to those on the full-scale plant. In this plant, the spray boxes are fed from a circular manifold, whereas in the model for convenience they were connected in series, but no appreciable pressure drop between sets of sprays was anticipated. General dimensions of the absorption chamber are given in Fig. 3(c). An antivortex baffle of cruciform shape was inserted at the base of chamber to reduce liquid swirl.

EXPERIMENTAL

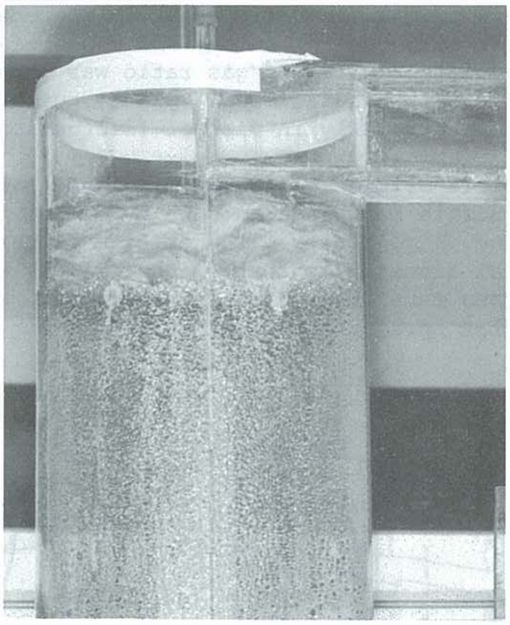
(a) Flow pattern

Air was drawn in through the scrubber at a rate of 11.0 ± 0.3 l s^{-1}. Mains water was fed to the manifold at a rate of 1.28 l s^{-1}. Water leaks were persistant at the points where the initially demountable spray-box assemblies fitted into the chamber, and these were eventually cemented in place.

It was important to establish whether the gas-flow path was spiral and, if so, whether the main gas flow passed through the sprayed zone. Air was bubbled through wash bottles containing successively concentrated hydrochloric acid and strong ammonia solution, and dense white fumes of ammonium chloride evolved were admitted to the main air supply. While the fumes were clearly visible in the inlet and outlet ducting, they became too diffuse within the main body of the scrubber to discern the flow pattern. Other tracing materials were tried, such as sawdust and fine talc. The latter was reasonably effective in picking out the general swirling pattern of the air (Fig. 4(a)). Repeated injections of talc caused a preferential accumulation of talc on the chamber wall adjacent to the main air-path and also at the spray-box assemblies. These tests indicated that the upper two fan-sprays did not impinge on the upward gas vortex, but covered a zone somewhat below it. The gas appeared to execute one and a half turns from inlet to outlet, as expected.



(a)



(b)

Fig. 4 (a) Gas-flow pattern, talc as tracer. (b) Effect of glass-fibre pad as a disentraining device.

With water on the sprays, considerable entrainment of mist was noted, and evidence of similar problems was available from full-scale operation. About 40 ml h^{-1} of liquid were drained off from the outlet ducting. A mist-impingement pad was made up from a 75 mm thick wad of fibreglass insulating material and was installed in the chamber just below the gas outlet. As shown in Fig. 5(b), the pad did the required job of collecting and coalescing the majority of the mist particles, so that the larger droplets were able to fall back into the upflowing airstream. A considerable flow of coalesced particles down the wall can be seen.

Another malfunction occurred close to the air inlet. When the sprays were turned on, the "horns" on the edges of the fan-spray sheets extended across the chamber on to the opposite wall. The effect became troublesome in that the inlet ducting became filled with water to a depth of about 10 mm. To prevent this accumulation, a small sloping shield was fitted within the duct, which eliminated all but the finest sprayed droplets. A drain plug was fitted to the duct to draw off the small deposits from time to time.

The cruciform baffle to inhibit the formation of a free vortex in the liquid at the base of the chamber appeared to be entirely successful.

(b) Absorptive performance

A measure of the effectiveness of the device is the absorptive performance, as indicated, for example, by the NTU. Sulphur dioxide was chosen as a substitute contaminant on the grounds of availability, limited solubility in water, ease of analysis and moderate toxicity hazards. The gas was introduced into the air-inlet duct under pressure, and gas samples were taken either at the air outlet or in the control axis of the chamber with a shielded probe to prevent mist entrainment. By raising or lowering the probe it was possible to obtain samples throughout the whole axial height of the chamber.

Gas samples were withdrawn at a rate of 15 ml s^{-1} through a Dreschel bottle containing 15 ml of 100 vol hydrogen peroxide solution and 60 ml of isopropanol with a few drops of thorin indicator added. After absorption, the solution was titrated against barium perchlorate solution that had been standardised against sulphuric acid solution (10 mol m^{-3} concentration). The endpoint was reached when the colour of the solution changed from yellow to pink. The concentration of dissolved sulphur dioxide was determined in the same way. However, since the analysis is sensitive to the presence of cations, a back-titration technique was adopted. A 5 ml sample was employed, and the procedure repeated using 5 ml of tap water. The difference in titres represented the sulphur dioxide present.

Performance results are summarized below. Since the equilibrium solubility of sulphur dioxide is linear with concentration at concentrations of 250 mg m^{-3} and less (the concentration levels chosen) (12), the expression for the NTU becomes

$$\text{NTU} = \int_{y_{A1}}^{y_{A2}} \frac{dy_A}{(y_A - y_A^*)} = \ln \frac{(y_{A2} - y_{A2}^*)}{(y_{A1} - y_{A1}^*)}, \quad y_A \ll 1 \tag{4}$$

	normal	water rate decreased		jets 5 and 6 shut off	with mist collector	
Air rate/g s^{-1}	14.6	13.9	13.7	14.75	14.3	14.3
Liquid rate/ml s^{-1}	97.5	85.8	86.7	71.7	100.8	100.8
Pressure drop/kPa	1	1		1	2.5	2.5
NTU	1.42	1.23	1.11	1.98	1.61	1.60

These data confirm the significant influence of the jet behaviour on the overall absorption and the desirability of installing a mist collector to reduce carryover of liquid droplets. For a two-stage system, these data suggest an overall efficiency of 90%, and one of 97% when the jets entirely scrub the main gas stream.

Care should be exercised in interpreting these results in the operation of full-scale plant, particularly as the siliceous deposits rapidly wear the nozzles so altering the spray characteristics and the physical properties of the liquor differ from those of tapwater. Nevertheless, the tests suggest that the upper nozzles may not be as effective as those positioned closer to the air inlet and that some disentrainment device in the second stage could be advantageous.

REFERENCES

1. Pullen, D., Dept of Health, priv. comm. (1974)
2. Strauss, W., "Industrial Gas Cleaning", p 91, Pergamon Press, Oxford (1966)
3. Hobler, T., "Mass Transfer and Absorbers", p 388, Pergamon Press, Oxford (1966)
4. Whynes, A.L., Trans. IChE (London), 34, 118 (1956)
5. Fraser, R.P., P. Eisenklam, N. Dombrowski and D. Hasson, A.I.Ch.E. Journal, 8, 672 (1962)
6. Hoftyzer, P.J. and D.W. van Krevelen, IChE Symposium on Gas Absorption, 32, S45 (1954)
7. Dombrowski, N. and P.C. Hooper, Chem. Eng. Sci., 17, 291 (1962)
8. Perry, H.E., ed., "Chemical Engineers' Handbook", 4/e, 18-65, McGraw-Hill, New York (1962)
9. Johnstone, H.F. and M.H. Roberts, Ind. Eng. Chem., 41, 2417 (1949)
10. Strauss, W., op. cit., p 318
11. Dombrowski, N. and W.R. Johns, Chem. Eng. Sci., 18, 203 (1963)
12. Pearson, D.A., L.A. Lundberg, F.B. West and J.L. McCarthy, Chem. Eng. Prog., 47, 257-64 (1951)

NOMENCLATURE

C_O	orifice-discharge coefficient	1
d_{vs}	volume-surface mean diameter of drop	m
D_C	chamber diameter	m
D_O	orifice diameter	m
h	fan-sheet thickness	m
h'	fan-sheet thickness at break-up	m
K	fan-sheet parameter	m^2
u_O	inlet-gas velocity	$m\ s^{-1}$
U_S	fan-sheet velocity	$m\ s^{-1}$
x	distance from nozzle	m
y_A	mass fraction of soluble gas	1
$y_A{}^*$	equilibrium mass fraction	1
ΔP	pressure drop	Pa
λ	wavelength of ripples on sheet	m
ν	kinematic viscosity	$m^2\ s^{-1}$
ρ_L	liquid density	$kg\ m^{-3}$
ρ_G	gas density	$kg\ m^{-3}$
σ	surface tension	$J\ m^{-2}$
θ	angle subtended by sheet at orifice	rad