Chemical Engineering Journal 84 (2001) 15–21

Chemical Engineering Journal

www.elsevier.com/locate/cej

The unsparged power demand of modern gas dispersing impeller in boiling liquids

John M. Smith [a,*], Zhengming Gao [a], J.C. Middleton [b]

[a] Department of Chemical and Process Engineering, School of Engineering in the Environment, University of Surrey, Guildford GU2 7XH, UK

[b] BHR Group, Cranfield, Bedford MK43 0AJ, UK

Received 15 December 1999; received in revised form 21 August 2000; accepted 23 August 2000

Abstract

It is known that impellers operating in boiling or near boiling liquids can develop cavities similar to those observed in gas–liquid systems at ambient temperatures. Considerable reductions in the power demand of traditional impellers operating in unsparged boiling liquids compared with that at ambient temperature have previously been reported and linked to a submergence based agitation cavitation (Smith) number. The performance of high performance gas dispersing impellers operating in boiling liquids has not previously been reported, despite their widespread adoption for mixing and dispersion in chemical reactors.

The power demand of selected modern impeller designs (Chemineer CD-6 and BT-6, Lightnin A315 and an impeller based on the ICI Gasfoil design) working in boiling liquids is reported, together with updated information about conventional Rushton and pitched blade turbines. In boiling liquids the power draw characteristics of the new designs are quite different from those of the traditional impeller types. The modern impellers are all efficient at handling high loadings of inert gases. In boiling liquids they maintain high levels of power input — even when operated with high impeller tip speeds that correspond to low cavitation numbers. Such cavitation as may occur clearly does not affect the power demand. The results are of particular relevance to the design and operation of forced circulation crystallisers when secondary nucleation, or the degradation of a particulate product, might be expected to follow cavitation.

Keywords: Mixing impellers; Agitated boiling; Boiling reactors; Power draw; Cavitation

1. Introduction

The requirements of processes that depend on the dispersion of large volumes of gas or vapour have led to the development of a variety of impeller patterns in recent years. It is well known that the power draw in a mechanically agitated gas–liquid system is usually below that for the same impeller driven at the same speed in unaerated liquid. With conventional impellers, e.g. a Rushton six-blade disc turbine, this relative power demand (RPD) may fall to as little as 0.4 as the flooding point is approached. It has been realised that dispersion and mass transfer performance would generally be enhanced if high power levels can be maintained. At the same time significant effort has been put into the development of impellers with a greater capacity to handle gas before flooding.

Impellers that have been successful in these objectives fall into two main categories. Early hollow blade designs were described by van't Riet et al. [1], Warmoeskerken and Smith [2], and Frijlink et al. [3]. These have been superseded by commercial deep hollow blade patterns, notably the SCABA [1] SGDT impeller used by Nienow [4,5] and Saito et al. [6], the ICI Gasfoil [2] [7] and the Chemineer [3] CD-6 [8] and BT-6 [9] designs.

The other approach to gas handling is exemplified by the low drag, wide chord, hydrofoil impellers referred to as having high solidity (i.e. with little free area in the projected plan, ostensibly to ensure that all gas passing upward through the impeller is bound to encounter one of the blades). Typical patterns are the Prochem [4] Maxflo T [10], the Lightnin A315 [5] [11] and the APV-B2 [5]. In cool systems these modern designs all offer dramatic improvements in gas handling performance.

* Corresponding author. Tel.: +44-1483-259276; fax: +44-1483-509276.
E-mail address: j.smith@surrey.ac.uk (J.M. Smith).

[1] SCABA AB, Stockholm.

[2] ICI plc have not to date made this impeller available to other potential users.

[3] Chemineer Inc. Dayton, OH.

[4] Now Chemineer Inc. Dayton, OH.

[5] Mixing Equipment Corporation, Rochester, NY.

1385-8947/01/$ – see front matter
PII: S1385-8947(00)00267-9

Nomenclature

A, B	constants in Eq. (1)
D	impeller diameter (m)
g	acceleration due to gravity (m s^{-2})
H	fill height of liquid in vessel (m)
N	impeller speed (s^{-1})
P	power draw of impeller (W)
P_B	power draw of impeller in boiling liquid (W)
P_U	power draw of impeller under ungassed or non-boiling conditions (W)
RPD	relative power demand, P_B/P_U
S	impeller submergence below free surface (m)
Sm	agitation cavitation (Smith) number, $2Sg/v_t{}^2$
T	vessel diameter (m)
v_t	impeller tip speed, $2\pi N$ (m s^{-1})

Greek letter

ρ	liquid density (kg m^{-3})

Cavitation is known to have a profound influence on the operation of impellers working in liquid with high vapour pressure, and the dynamics of impellers in boiling systems are significantly different than they are when operating in liquids with low vapour pressure.

Previous work on mechanically agitated boiling reactors has concentrated on more or less conventional Rushton and pitched blade impellers and their immediate derivatives. The question arises as to whether the modern impeller designs have similar behaviour and how the improvements in gas handling capacity are reflected when operating in vapour liquid systems. Before approaching the problems of hot sparged systems, which arise most often in industrial applications, it is necessary to develop descriptions of their performance in unsparged boiling liquids. This topic provides the theme of the present paper.

Smith and Katsanevakis [12] published data on the performance of several common impellers in boiling liquids. By analogy with the conventional hydrodynamic cavitation number, the RPD was characterised in terms of an agitation cavitation (Smith) number, Sm, based on the impeller submergence S and tip speed v_t. (The Institute of Chemical Engineers Fluid Mixing Processes Group has recently approved a suggestion that this dimensionless group should be called the Smith number, Sm, which notation will be followed here). Cavitation will only occur when the local pressure falls below the vapour pressure of the liquid. If a submerged impeller is rotating slowly, this condition is unlikely to be met. The speed it has to be driven before cavitation starts depends on its shape and the flow field that is developed. Each impeller type has a characteristic critical cavitation number below which cavitation may occur. It is beyond this point that the RPD is found to decrease in a similar way, but generally less spectacularly, to that in cold gassed systems.

Below the relevant characteristic cavitation number, Smith and Katsanevakis [12] found that for all the impellers they studied that RPD followed a relationship of the form:

$$\mathrm{RPD} = A\left(\frac{Sg}{(1/2)v_t^2}\right)^B \qquad (1)$$

The group in the bracket is the agitation cavitation (Smith) number, Sm, the constant A depends on the impeller geometry and appears to be virtually independent of scale or the D/T ratio of the reactor. A is related to cavity development, specifically A is markedly higher for a pitched blade impeller than for a Rushton turbine which has low pressure regions, where cavitation can more easily start, behind the blades. For all the impellers studied by Smith and Katsanevakis [12] the exponent B was about 0.4.

Since consideration is limited to turbulent systems, viscosity is not expected to be a significant variable. Density is also unimportant since it occurs in both the "ρgh" term of the numerator (the difference between the local hydrostatic pressure and the vapour pressure of the liquid — which is boiling at the free surface) and in the "$\frac{1}{2}\rho v^2$" term of the denominator. It must however be pointed out that this argument ignores the reduced mean bulk density above the impeller plane. The role of impeller submergence was unequivocally established by Katsanevakis [13]. This has allowed the present work to be limited to a single fixed impeller depth. A subsequent note by Smith and Tarry [14] demonstrated that vapour pressure also has no significant influence at least with aqueous solutions. It has been concluded therefore that relations like Eq. (1) should provide a simple and adequate basis to characterise cavitation in turbulent boiling mixing vessels, whatever the process fluid.

2. Experimental

The equipment used in this study was essentially that used by Smith and Katsanevakis [12]. This is a conventional ($H = T$), 0.45 m diameter, baffled tank with a dished base in which three electric immersion heaters are mounted (Fig. 1).

The new heaters have a higher heat rating and are somewhat longer than the original ones. They therefore interact differently with the discharge from radial impellers. This means that both the ungassed and boiling power demand levels are slightly different from those reported in the earlier work. The data for a Rushton turbine given below illustrates the small differences involved. The shaft carrying the impellers has a Vibro-torque meter to measure shaft power and impeller speed. In this work the impellers were always mounted at a submergence of 0.3 m. The details of the impellers used are as follows.

The conventional Rushton turbine with an overall diameter of 0.18 m (Fig. 2) was same as that used by Smith and Katsanevakis [12]. The conventional 4–45° pitched blade turbine (Fig. 3) was used in the experiments.

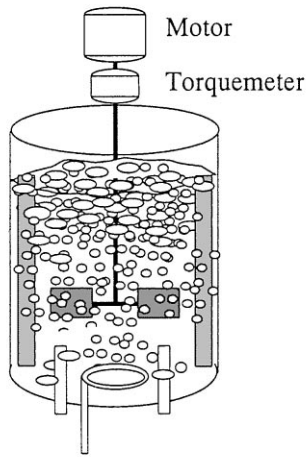

Fig. 1. Sketch of the equipment.

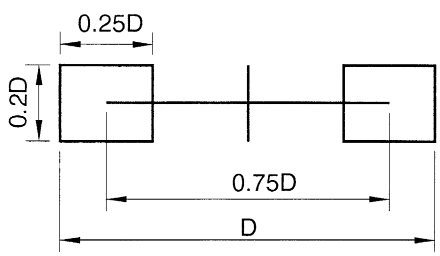

Fig. 2. Rushton turbine.

The hollow blade impeller used by Smith and Katsanevakis [12] had blades with a 90° subtended angle. Several later developments of blade profile based on the same principle. The Chemineer CD-6 (Fig. 4) has six blades of semicircular cross-section, i.e. having a subtended angle of 180°.

The ICI Gasfoil, developed earlier, uses a similar principle with a blade profile that is essentially a symmetrical

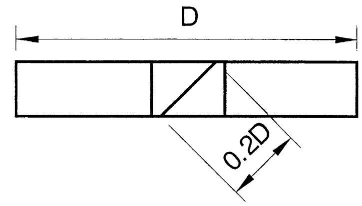

Fig. 3. 4–45° pitched blade turbine (PBT).

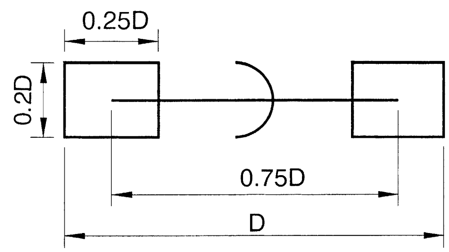

Fig. 4. Chemineer CD-6 impeller.

semi-ellipse [7]. For the present work a six blade version which does not have a disc (Fig. 5) was used. The latest design from Chemineer, known as the Bakker turbine, BT-6 (Fig. 6), has disc mounted blades of an asymmetric semi-elliptical cross-section, with the upper surface extended in order to enhance the gas capturing profile [9].

Early attempts to develop impellers of low power number led to relatively narrow hydrofoil based designs of short chord length. While being very efficient liquid movers, these designs were ineffective in handling gas–liquid mixtures. The Lightnin A315 (Fig. 7), is one of several wide blade patterns that have successfully been used for these applications. Recent work by Hari-Prajitno et al. [15] has confirmed that when operated in an upward pumping mode,

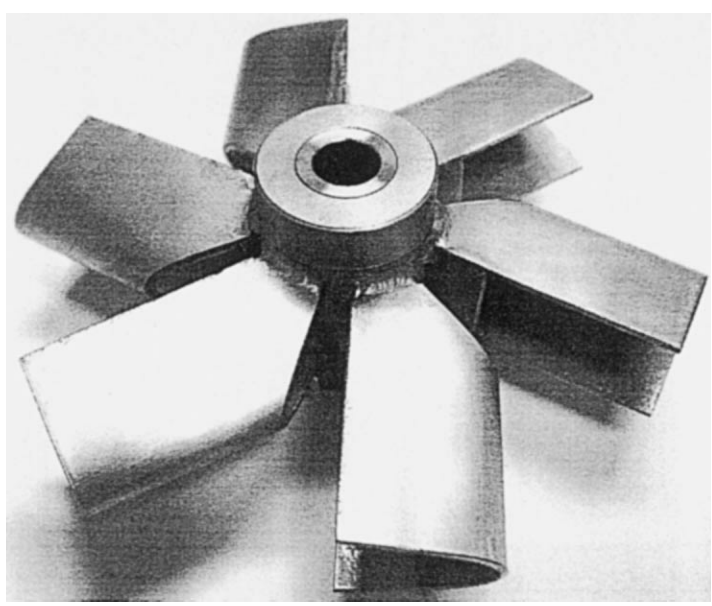

Fig. 5. ICI GF impeller.

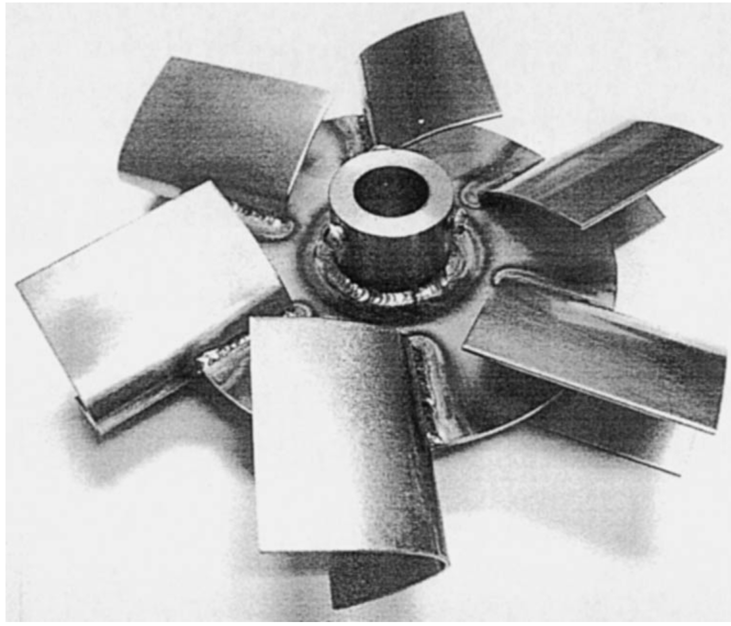

Fig. 6. Chemineer BT-6 impeller.

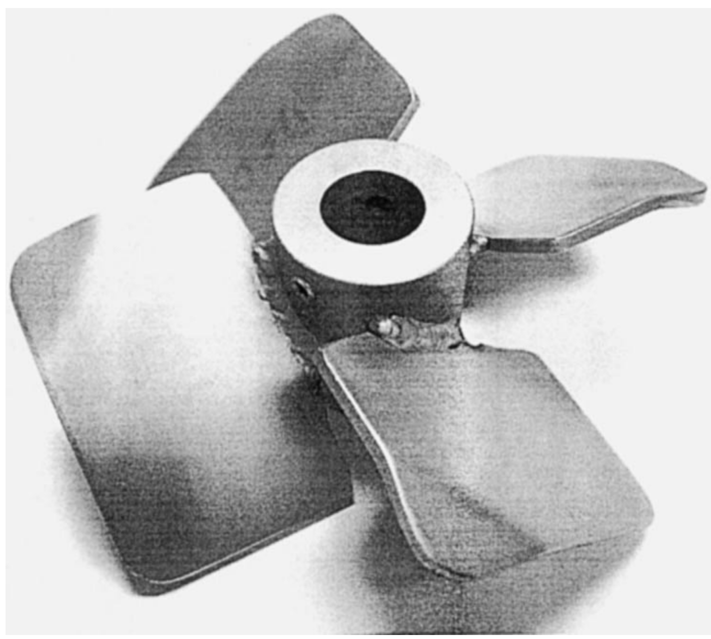

Fig. 7. Lightnin A315 impeller.

APV-B2 impellers are particularly efficient at handling extreme gas loadings. In view of that, and the large volumes of vapour that may be generated, we have included this mode of operation with the A315 used in present study.

The somewhat changed geometry of the vessel necessitated the determination of new reference values for the ungassed turbulent power numbers. These were determined both at room temperature and also at around 90°C to ensure that no errors were arising simply as a result of an unsuspected temperature dependence. The appropriate density of the water was used for the calculations. Table 1 details these results.

3. Results and discussion

3.1. Rushton turbine

The dependence of the RPD of a Rushton turbine on the agitation cavitation number is shown in Fig. 8.

Table 1
Ungassed fully turbulent power numbers

Impeller type	Impeller diameter (m)	Power number	
		Room temperature	Elevated temperature
Rushton turbine	0.18	5.41	5.44
4∗45° pitched blade, up	0.18	1.08	1.08
4∗45° pitched blade, down	0.18	1.08	1.08
Chemineer CD-6	0.176	2.75	
ICI Gasfoil 6 (no disc)	0.137	1.86	
Chemineer BT-6	0.177	2.19	
Chemineer HE-3	0.178	0.27	
Lightnin A315, up	0.137	1.34	
Lightnin A315, down	0.137	1.34	

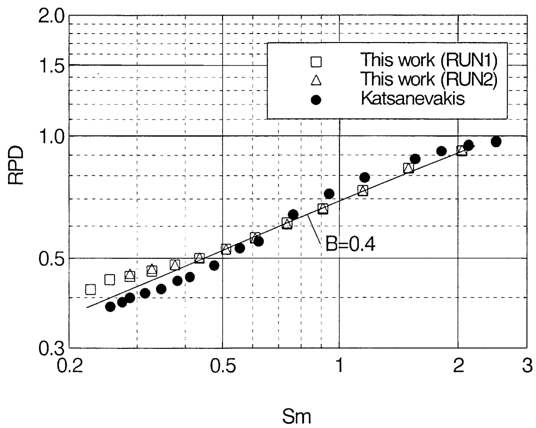

Fig. 8. RPD for a Rushton turbine.

The results shown include original data from Katsanevakis [13] which are compared with values obtained in the slightly modified reactor. The agreement is generally good. That being said, all the experimental data below the critical cavitation number cluster around the straight line, which has the equation:

$$\mathrm{RPD} = 0.7\, Sm^{0.4} \tag{2}$$

There is a clear tendency for the data points to fall above the mean line at the highest and lowest values of *Sm*. Under these conditions the absolute accuracy of the measurements is limited by the possibility of surface draw-down of air. Smith and Millington [16] have shown that such draw-down would modify the RPD significantly. The reproducibility of the data is clearly demonstrated by the replicate measurements shown in the figure.

3.2. Pitched (four) blade turbine (PBT)

Fig. 9 shows the results for the turbine for both upward and downward pumping operation. There are some differences from the down-pumping data presented by Smith and Katsanevakis [12]. The main reason for this is thought not to lie in the smaller diameter of the present impeller but in

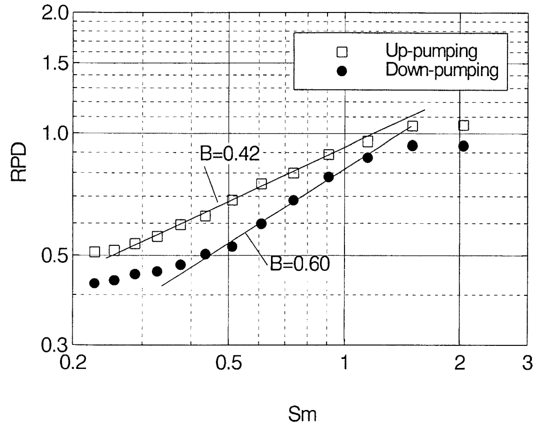

Fig. 9. RPD for 4–45° PBT.

differences in their detailed geometry. The present impeller has four conventional blades compared with the earlier one, which had six rather wide blades. For the down-pumping mode the RPD curve confirms the slope of about 0.4, albeit with some uncertainty, and the critical cavitation number of a pitched blade turbine in the present results is seen to be much closer to that of a Rushton impeller than the previous results implied. A similar reduction in cavitation is found in the wide blade hydrofoil results presented below.

In the up-pumping mode performance is significantly different. The configuration has the advantage that buoyancy forces are acting to reinforce the impeller pumping, so avoiding the inherent conflict between rising gas and downward moving liquid. The RPD/*Sm* line again confirms the slope of 0.4 and the critical cavitation number is much lower at about 1.25 instead of 2.0. As with the Rushton turbine the points relating to the data at highest speed deviate upwards. The possibility of some entrainment of air from the free surface cannot be excluded for either configuration since it is known that draw-down of floating solids is even more effective with up-pumping pitched blade turbines than when they are used in down-pumping mode [8].

As a practical point it should be emphasised that to operate a pitched blade impeller in upward pumping mode it may be necessary to do more than simply reverse the direction of rotation of the impeller shaft. A hydrofoil impeller will have a cambered surface so the impeller must also be inverted. Mixer gearboxes are usually designed to operate in a particular direction. The bearing loads will also be altered when a downward reaction force on the assembly replaces the upthrust that partially supports the weight of a down-pumping impeller.

3.3. Chemineer CD-6

The disc mounted hollow blades of the CD-6 impeller, Fig. 4 above, have a projected area similar to that of a Rushton turbine of the same diameter. Some of the commercially available versions have blades that can be moved inwards or

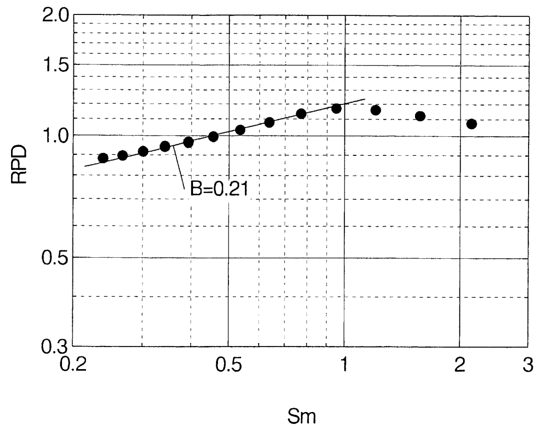

Fig. 10. RPD∼*Sm* dependence for a Chemineer CD-6 impeller.

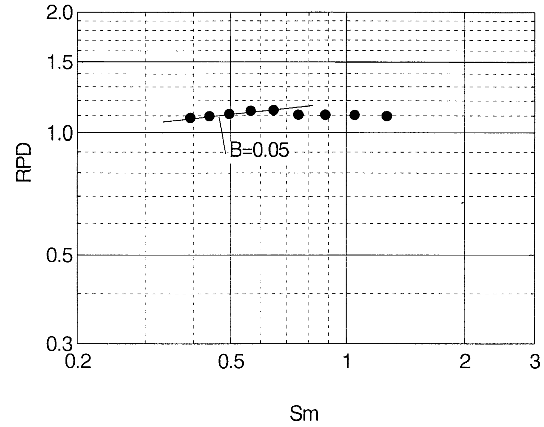

Fig. 11. RPD∼*Sm* dependence for an ICI GF impeller.

outwards, allowing the impeller power demand to be closely matched to the system specification and process requirements.

The characteristic RPD line for this hollow blade impeller was found to be different from all those studied in the previous work. The exponent B of Eq. (1), i.e. the slope of the log–log plot of RPD vs. Sm line, deviates from 0.4; Fig. 10 shows the results. In order to facilitate comparisons we have chosen to use the same (non-isotropic) scale for all the figures.

As the impeller is started from rest and the speed slowly increased, the RPD rises above that measured in cold or hot, non-cavitating, liquid, before falling as the agitation cavitation number (which is proportional to the reciprocal of the square of the impeller speed) is further decreased.

The critical cavitation number is difficult to define rigorously. The maximum in the RPD curve, which is about 15% above the ungassed level, is at a cavitation (Smith) number of about 1.0 but P_B actually falls below P_U only when Sm is less than about 0.5. In this case again the line has a slope of about 0.2. The higher power transmission to the liquid implies that the pumping capacity and turbulence generation is less impaired in the hot system than with a conventional turbine, presumably because cavitation has been delayed.

3.4. ICI GF type

Although some Gasfoil impellers have disc mounted blades, the version used in the present work had six blades mounted directly from the hub as is shown in Fig. 5. The RPD line is almost flat for this impeller, though as can be seen in Fig. 11, at low speeds it is slightly above the "standard" ungassed level with a tendency for the RPD to fall with an exponent of 0.2 at the lowest cavitation numbers, as is the case with the CD-6. This maintenance of the power level in boiling liquid is consistent with the ability of this impeller to handle large gas volumes.

3.5. Chemineer BT-6

This newest addition to the Chemineer range is claimed to have outstanding gas handling capacity. As shown in Fig. 6. the disc mounted blades are asymmetric. This will make it very suitable for applications in which gas generation or the vaporisation of liquid into sparged gas will be occurring.

In unsparged boiling liquid the power draw is maintained slightly above the corresponding cold power number down to the lowest values of cavitation number that could be achieved in the present equipment (Fig. 12). As with the CD-6 and Gasfoil impellers, there is some suggestion that under the most extreme conditions the RPD is beginning to fall.

3.6. Lightnin A315

This wide chord hydrofoil has been used successfully in many gas dispersion applications, including several reactors in which suspension is solid required at the same time. Recent work by Hari-Prajitno et al. [15] has demonstrated the effectiveness of APV-B2 impeller in upward pumping mode.

As can be seen from Fig. 13, the RPD/*Sm* lines are again very flat both in upflow and in downflow modes. It should

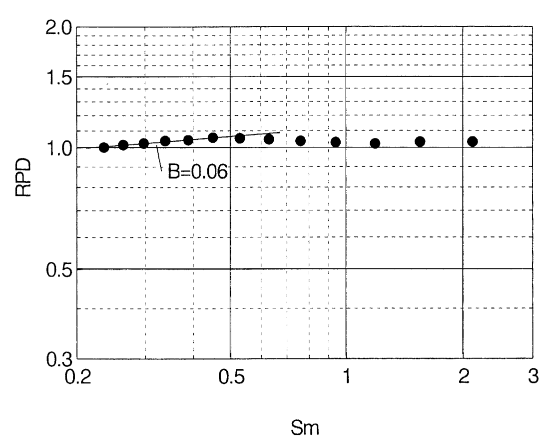

Fig. 12. RPD∼*Sm* dependence for a Chemineer BT-6 impeller.

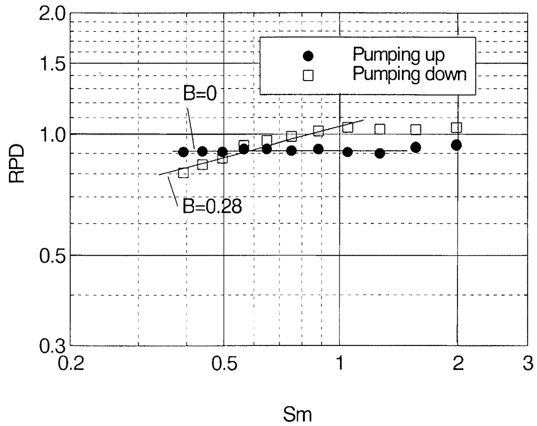

Fig. 13. RPD∼*Sm* dependence for a Lightnin A315 impeller.

be noted that the impeller was inverted and the direction of rotation reversed for the upflow measurements. In this up-pumping mode the performance of this A315 is expected to be similar to that of the lighter, three bladed, Lightnin A340 which is designed with blades mounted with the opposite pitch so that it pumps upwards when, as seen from above, it is driven clockwise.

The A315 cavitates only with difficulty, the critical cavitation (Smith) number for this impeller is about 0.9 when down-pumping, below this point the slope of the RPD/*Sm* line is, like most other impeller types, about 0.4. When up-pumping this wide chord hydrofoil maintains a power demand corresponding to ungassed conditions and does not appear to cavitate at all. If a critical cavitation number exists in upflow, it is outside the range studied.

4. General conclusions

All the modern gas-dispersing impellers work effectively in boiling liquids, maintaining a relative power demand that is close to that in ungassed liquid up to quite high tip speeds. In several cases the operating power demand at low impeller speeds is somewhat (10–15%) higher than in standard ungassed conditions and it has so far not been possible to put forward any convincing explanation for this observation.

Table 2
Summary of results: cavitation (Smith) numbers and tip speeds ($m\,s^{-1}$)

Impeller type	*Sm*		Slope *B*	Tip speed at $S = 0.65$ m	
	Maximum	Critical		Initiation	Sub-critical
Rushton	4.0	2.5	0.40	1.8	2.3
CD-6	1.0	0.5	0.21	3.7	5.2
BT-6	0.4	0.2	0.06	5.3	7.4
Gasfoil	0.6	0.3	0.05	4.5	7.1
PBT 45∗4D	1.5	2.0	0.60	2.9	2.5
PBT 45∗4U	1.5	1.25	0.42	2.9	3.2
A315 D	1.0	0.9	0.28	3.5	3.8
A315 U	<0.4	<0.4	0	>5.7	>5.7

This perhaps reduces the validity of the definition of the critical agitation cavitation (Smith) number as that when the power demand falls below the ungassed requirement. Accordingly we summarise the results in Table 2 in terms of the cavitation (Smith) number at which the power demand goes through the maximum as well as that at which it falls below the ungassed value. In order to assist interpretation we also present these data in terms of the corresponding impeller tip speeds at a submergence of 0.65 m, intended to be appropriate for reactors of around 1 m in diameter.

Acknowledgements

Grateful acknowledgement is made to ICI for the financial and technical support of this work and to Chemineer for the supply of impellers.

References

[1] K. van't Riet, J.M. Boom, J.M. Smith, Power consumption, impeller coalescence and recirculation in aerated vessels, Chem. Eng. Res. Des. 54 (1976) 124–131.
[2] M.M.G.G. Warmoeskerken, J.M. Smith, The hollow blade agitator for dispersion and mass transfer, Chem. Eng. Res. Des. 67 (1989) 193–198.
[3] J.J. Frijlink, A. Bakker, J.M. Smith, Suspension of solid particles with gassed impellers, Chem. Eng. Sci. 45 (1990) 1703–1718.
[4] A.W. Nienow, Gas dispersion performance in fermenter operation, Chem. Eng. Progr. 86 (2) (1990) 61–71.
[5] A.W. Nienow, Gas–liquid mixing studies: a comparison of Rushton turbines with some modern impellers, Chem. Eng. Res. Des. 74 (1996) 417–423.
[6] F. Saito, A.W. Nienow, S. Chatwin, I.P.T. Moore, Power, gas dispersion and homogenisation characteristics of Scaba SRGT and Rushton turbine impellers, J. Chem. Eng. Jpn. 25 (1992) 281–287.
[7] J.C. Middleton, Agitators, US Patent 5,198,156 (1993).
[8] A. Bakker, J.J. Frijlink, The drawdown and dispersion of floating solids in aerated and unaerated stirred vessels, Chem. Eng. Res. Des. 67 (1989) 208–210.
[9] K.J. Myers, A.J. Thomas, A. Bakker, M.F. Reeder, Performance of a gas dispersion impeller with vertically asymmetric blades, Chem. Eng. Res. Des. 77 (1999) 728–730.
[10] Z. Jaworski, A.W. Nienow, K.N. Dyster, An LDA study of the turbulent flow field in a baffled vessel agitated by an axial, down-pumping hydrofoil impeller, Can. J. Chem. Eng. 74 (1996) 3–15.
[11] J.Y. Oldshue, Fluid mixing in 1989, Chem. Eng. Progr. 85 (5) (1989) 33–42.
[12] J.M. Smith, A. Katsanevakis, Impeller power demand in mechanically agitated boiling systems, Chem. Eng. Res. Des. 71 (1993) 145–152, 466.
[13] A. Katsanevakis, Performance parameters for boiling and gassed stirred tank reactors, Ph.D. Thesis, The University of Surrey, Guildford, UK, 1994.
[14] J.M. Smith, K. Tarry, Impeller power demand in boiling solutions, Chem. Eng. Res. Des. 72 (1994) 739–740.
[15] D. Hari-Prajitno, V.P. Mishra, K. Takenaka, W. Bujalski, A.W. Nienow, J. Mckemmie, Gas–liquid mixing studies with multiple up- and down-pumping hydrofoil impellers: power characteristics and mixing time, Can. J. Chem. Eng. 76 (1998) 1056–1068.
[16] J.M. Smith, C.A. Millington, Boil-off and power demand in gas–liquid reactors, Chem. Eng. Res. Des. 74 (1996) 424–430.