Effect of Blade Shape on Unsteady Mixing of Gas-Liquid Systems

Sebastian Frankiewicz and Szymon Woziwodzki

1 Introduction

Mechanical mixing is one of most commonly used unit operations in the industry. It is conducted usually within turbulent flow regime in stirred vessels equipped with baffles. This mixing method in some processes is not recommended due to the presence of baffles. This applies to, for example, the pharmaceutical industry where particular attention is paid to cleanliness of apparatus (Yoshida et al. 2001a; Woziwodzki 2017). Turbulent mixing in stirred vessels without baffles causes many problems due to the primary circulation which results in lower mixing power and longer mixing time. For this reason, one of the major aspects in such systems is to improve the intensity and efficiency of mixing. Few methods can be used to achieve this, such as: eccentric positioning of the impeller and unsteady motion. In first solution, the impeller's position $E/R \approx 0.5$ generates higher power demand and improved intensity and efficiency of mixing (Karcz et al. 2005; Montante et al. 2006; Woziwodzki et al. 2010; Woziwodzki and Jędrzejczak 2011; Ng and Ng 2013). In the second solution, the unsteady motion of the impeller can be done in two ways: by reciprocating motion and by unsteady rotation of impeller. During reciprocating motion the impeller moves along vertical axis of the stirred vessel. These are usually disk impellers, disk impellers with flapping blades or impellers with complex dimensions depending on oscillation amplitude (Masiuk 1999, 2000, 2001; Komoda et al. 2000, 2001; Kamieński and Wójtowicz 2001, 2003; Masiuk and Rakoczy 2007; Masiuk et al. 2008; Wójtowicz 2012; Kordas et al. 2013).

In case of unsteady rotation of the impeller in a stirred vessel there is no formation of a central vortex but higher mixing turbulence with greater stress around the impeller is observed (Yoshida et al. 2008, 2009, 2010; Woziwodzki 2017).

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Unsteady rotation can be performed in many ways but given the structural limitations, usually the sinusoidal, triangular and rectangular time-course of impeller speed is used.

2 Basic Equations

To describe forces that occur in unsteady mixing, Morison equation is used (Morison 1953) determining torque T on the shaft of a stirred vessel (Woziwodzki 2017)

$$T = \frac{1}{16} D^5 C_1 \rho C_D |\omega| \omega + \frac{\pi D^5 \rho}{16} C_1 C_I \frac{d\omega}{dt} \tag{1}$$

where D is impeller diameter, ω is angular speed of impeller, C_D is drag coefficient and C_I inertia coefficient.

By knowing the impeller speed and so the angular speed, equations describing the given type of unsteady motion are obtained, such as, for triangular time-course of impeller speed (Woziwodzki 2017)

$$\begin{aligned} T = {} & \frac{16}{\pi^2} C_1 C_D N_{\max}^2 D^5 \rho \left| \sin(2\pi ft) - \frac{1}{9}\sin(6\pi ft) + \frac{1}{25}\sin(10\pi ft) \right| \\ & \times \left(\sin(2\pi ft) - \frac{1}{9}\sin(6\pi ft) + \frac{1}{25}\sin(10\pi ft) \right) \\ & + D^5 \rho C_1 C_I N_{\max} \frac{d\left(\sin(2\pi ft) - \frac{1}{9}\sin(6\pi ft) + \frac{1}{25}\sin(10\pi ft)\right)}{dt} \end{aligned} \tag{2}$$

where $N_{\max}$ is the maximum impeller speed and f is the oscillation frequency.

Finding of the torque allows to determine the mixing power variation over time (Woziwodzki 2017)

$$\begin{aligned} P = {} & \frac{32}{\pi} C_1 C_D N_{\max}^3 D^5 \rho \left| \sin(2\pi ft) - \frac{1}{9}\sin(6\pi ft) + \frac{1}{25}\sin(10\pi ft) \right| \\ & \times \left(\sin(2\pi ft) - \frac{1}{9}\sin(6\pi f)t + \frac{1}{25}\sin(10\pi ft) \right) \\ & + 2\pi D^5 \rho C_1 C_I N_{\max}^2 \frac{d\left(\sin(2\pi ft) - \frac{1}{9}\sin(6\pi f)t + \frac{1}{25}\sin(10\pi ft)\right)}{dt} \end{aligned} \tag{3}$$

An essential issue in unsteady mixing is to determine the drag force and inertia force domination ranges. Unsteady mixing studies with triangular time-course of impeller speed (Woziwodzki 2017) show that these ranges can be described with a Keulegan–Carpenter number

$$KC = \frac{N_{\max}}{f} \tag{4}$$

In respect of Keulegan–Carpenter numbers higher than $KC = 15$ the drag force is dominant and in respect of $KC < 4$ the inertia force prevails and in range of $KC \epsilon < 4; 15>$ both forces are important. This allows modifying the Morison equation accordingly and abandoning its elements that describe the force which is not prevailing.

3 Unsteady Mixing of Gas-Liquid Systems

One of the basic goals of mixing of gas-liquid systems is to ensure the appropriate development of interfacial area. However, this faces obstacles which are, among others, related to the decreased mixing power demand. This is due to the lower density of the system (compared to uniform system) resulting from presence of gas. Lower mixing power, in turn, causes the reduction of interfacial area and thus lower intensity of mass transfer in a stirred vessel. In addition, mixing of these type of two-phase systems has a tendency to form gas cavities (Kamieński 2004; Middleton and Smith 2004). These are formed due to the presence of low pressure areas behind the impeller blades and result in lower mixing power, such as, by about 65% for Rushton turbine (Middleton and Smith 2004). Low pressure areas are formed due to the liquid flowing around the blades. They can be reduced by modifying the shape of blades. These zones, i.e. behind the hollow blades, are smaller which contributes to the higher mixing power, such as, decrease in mixing power is about 30% for CD-6 (Smith turbine) and about 20% for BT-6 impeller (Fig. 1) (Bakker 2000). It can be concluded that the use of hollow (unsymmetrical elliptic) blades (BT-6) gives better results than cylindrical blades (CD-6).

Mixing of two-phase systems is accompanied by other issues such as the presence of areas characterized by lower homogeneity degree right behind the baffles, flooding of impeller, uneven gas dispersion for impellers with higher diameters at low impeller speeds or a rare turbulence near interphase areas in stirred vessels with larger impellers (Yoshida et al. 2001b).

Considering these effects, there is a need to solve these problems with a new mixing method. Oscillations can be successfully used in Oscillatory Baffled

Fig. 1 BT-6 impeller

Column (OBC) or Oscillatory Baffled Reactors (OBR). This allows for a significant increase of mass transfer coefficients. Ni and Gao (1996) point that a nearly 5-time increase is observed for two-phase water-air systems in OBCs. The use of oscillation in fermentation also contributes to about two-time increased mass transfer coefficient. For this reason, oscillation of impeller speed can also contribute to more intensive mass transfer.

In gas-liquid systems and unsteady mixing, usually the typical parameters related to the miscible liquid systems are used, such as the relative mixing power demand RPD (P_g/P_u) or the relative drag and inertia coefficients. Drag coefficient for gas-liquid system C_{dg} depends on the gas content and decreases with the increase of Reynolds number for $Re_{um} < 300$. Above $Re_{um} = 300$, C_{dg} coefficient is constant and independent of Reynolds number. For gas-liquid systems, the drag coefficient can be (just as mixing power) shown as a relative drag coefficient C_{dg}/C_{du} (RDC). RDC coefficient is dependent on impeller speed, impeller diameter, oscillation frequency as well as gas flow rate. This dependency can be shown with a general equation (Woziwodzki 2017):

$$RDC = C_1 {Fl_{g,u}}^{C_2} {Fr_u}^{C_3} \tag{5}$$

where $Fl_{g,u}$ is unsteady gas flow number ($Fl_{g,u} = Q_g/fD^3$) and Fr_u is unsteady Froude number ($Fr_u = f^3D/g$).

In case of unsteady mixing (Fig. 2) the impeller speed changes constantly. This results in all regimes of gas-impeller interactions in a single oscillation cycle: from flooding to full dispersion. Therefore, the maximum mixing power P_{gmax} is important. Its determination requires determining time t after which P_g reaches its maximum value. For unsteady mixing with triangular time-course of impeller speed P_{gmax} can be determined with Eq. (6):

$$P_{gmax} = \frac{98.22}{\pi^2} C_1 C_{Dg} N_{max}^3 D^5 \rho \tag{6}$$

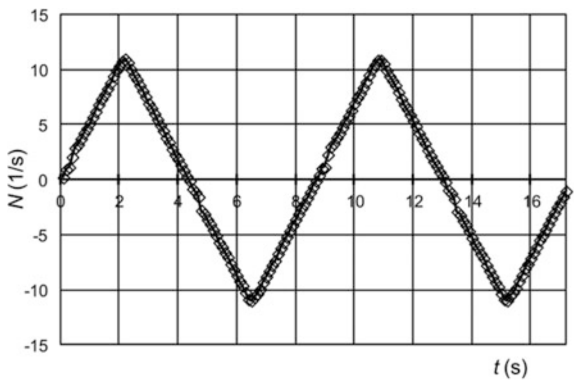

Fig. 2 Time-course of impeller speed for unsteady mixing (triangular wave)

The maximum mixing power number is determined with Eq. (7) (Woziwodzki 2017):

$$Ne_{g\max} = \frac{98.22}{\pi^2} C_1 C_{Dg} \tag{7}$$

and the ratio of mixing power $P_{g\max}$ and the average power is determined with Eq. (8) (Woziwodzki 2017):

$$\frac{P_{g\max}}{(P_g)_{av}} = 1.74\pi \tag{8}$$

Gas dispersion in a stirred vessel is affected by impeller type. Impellers with hollow, unsymmetrical blades (i.e. BT-6) are preferred to disperse larger amount of gas and work with higher gas load without flooding. However studies of unsteady mixing of two-phase gas-liquid systems in a stirred vessel with BT-6 are limited. There are also no data on the effect of the number of blades and their shape on gas dispersion. For this reason studies for air-water system for BT-6, BT-4 (Fig. 3) and BT-4E (Fig. 4) were conducted.

Unsteady mixing of miscible fluids is characterized by higher mixing power demand than steady mixing (Yoshida et al. 1999, 2001a; Woziwodzki 2011, 2017). Figures 5, 6 and 7 show the relation between power number *Ne* and Reynolds

Fig. 3 BT-4 impeller

Fig. 4 BT-4E impeller

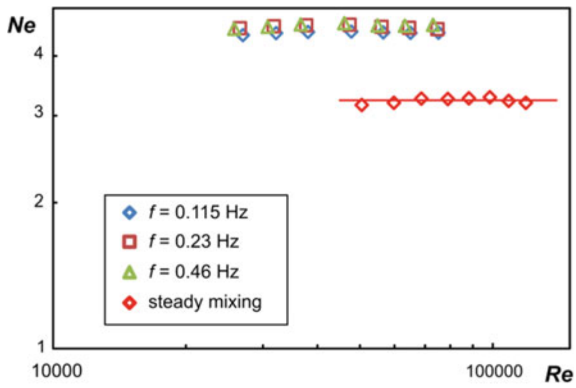

Fig. 5 Relation between unsteady power number and Reynolds number for BT-4E

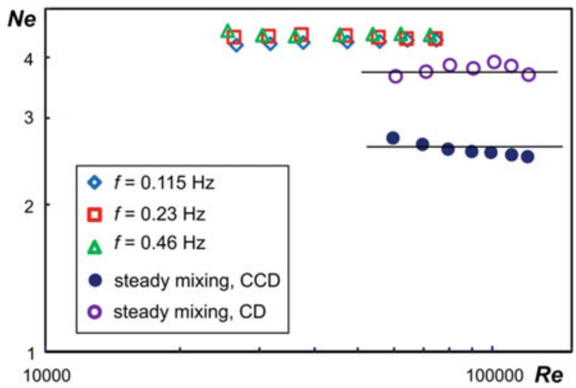

Fig. 6 Relation between unsteady power number and Reynolds number for BT-6; *CCD* counter-clockwise direction of rotation, *CD* clockwise direction of rotation

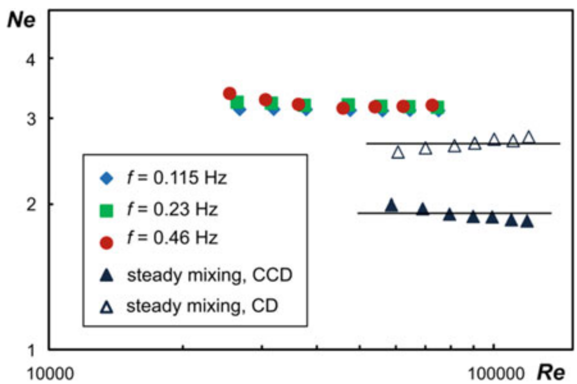

Fig. 7 Relation between unsteady power number and Reynolds number for BT-4

Table 1 Power number for unsteady mixing

Impeller	Power number
RT (Woziwodzki 2011)	7.14
ST (Woziwodzki 2011)	4.74
PBT (Woziwodzki 2011)	1.64
HE-3 (Woziwodzki 2017)	1.49
A315 (Woziwodzki 2017)	2.98
SC-3 (Woziwodzki 2017)	0.88

number *Re* for unsteady mixing. In all analyzed cases, oscillation frequency *f* does not affect the power number *Ne*. It was also observed for all impellers that the use of unsteady mixing caused increase in power demand in comparison to steady mixing. This increase was about 40% for BT-4E, about 16% for BT-6 and clockwise direction of impeller rotation (CD) and about 20% for BT-4 in relation to clockwise direction of rotation (CD). The increase in power demand is related to the need for changing the liquid circulation direction in a stirred vessel, which increases power demand, as well as related to higher drag force and larger disturbances are formed on both sides of blades. Exemplary power numbers for other impellers are shown in Table 1.

The highest turbulent power number was achieved for BT-4E impeller (*Ne* = 4.54), the lower power numbers were for BT-6 (*Ne* = 4.37) and BT-4 (*Ne* = 3.19) respectively.

The power number for BT-4E was higher about 42 and 4% in comparison to BT-4 and BT-6 impeller respectively.

The results obtained indicate that taking into account the unsteady mixing power demand, lower increase of power is observed, in relation to the steady mixing, for impellers with unsymmetrical hollow blades (BT-6, BT-4). These results imply that also for these impellers, the relative mixing power in gas-liquid systems should be lower. Figures 8, 9 and 10 show relation between RPD and gas flow number for the air-water system and BT-4E, BT-6 and BT-4 impellers.

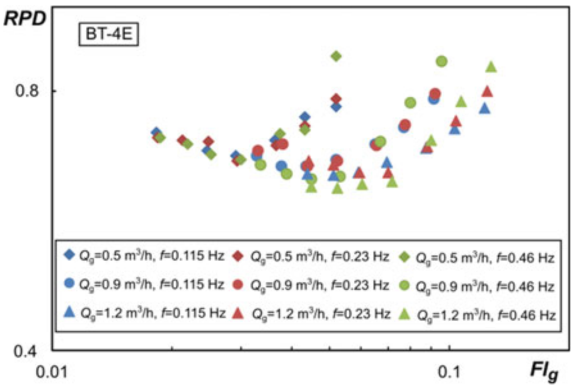

Fig. 8 Relation between relative power demand (RPD) and gas flow number for BT-4E impeller; air-water system

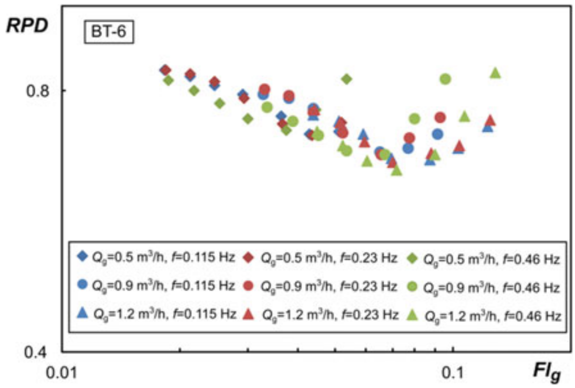

Fig. 9 Relation between relative power demand (RPD) and gas flow number for BT-6 impeller; air-water system

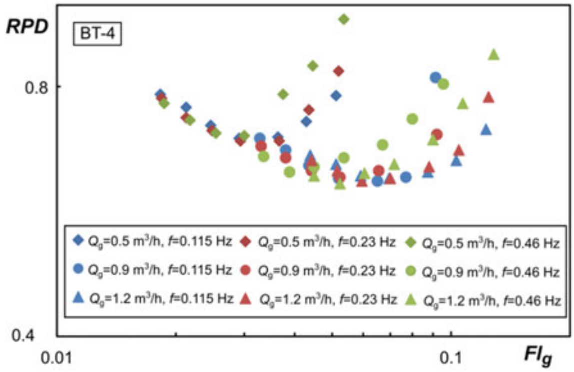

Fig. 10 Relation between relative power demand (RPD) and gas flow number for BT-4 impeller; air-water system

The analysis of unsteady mixing power $P_{g,u}$ in gas-liquid system shows that BT-4E impeller is characterized by much higher power demand than BT-4 for all tested gas flow rates, oscillation frequencies and impeller speeds. Comparing these results with BT-6, higher relative power compared to BT-4E at low speeds is observed. The impeller speed N range in which the power is higher for BT-4E is larger as the amount of supplied gas increases.

For impeller BT-4E (Fig. 8), an oscillation frequency affects RPD only slightly. With the increased impeller speed, the power initially drops and then starts to rise. This increase is lower in relation to BT-6 and BT-4 impellers. It is related to different types of gas cavities present behind the blades.

For BT-6 (Fig. 9), the effect of gas flow rate is smaller. The relative power demand decreases at low speeds and starts to rise rapidly after a certain impeller speed value is exceeded ($Fl_g < 0.07$) It is simply related to the reduction of gas cavities behind the blades. The data indicates that oscillation frequency affects the relative mixing power demand and it is notices for all gas flow rates. At low impeller speeds, the RPD is highest for highest oscillation frequencies and for higher impeller speeds, this dependence is smaller ($Fl_g < (0.04; 0.07)$).

In case of BT-4, as for other impellers, an initial decrease in relative power demand with the increase of impeller speed is observed and subsequent increase of power demand above a certain speed is observed, which is caused by changes of gas cavities. The oscillation frequency f also affects the RPD and is highest for highest oscillation rates but this dependence is smaller as the impeller speed increases. Highest relative power demand, at low impeller speeds, is noticed for BT-4E and at higher impeller speeds, for BT-6. This relation is valid for all gas flow rates. BT-6 impeller has the lowest power demand drop caused by supplied gas. BT-4E at higher impeller speeds for gas rate 0.5 m^3/h has the lowest RPD and in case of gas rates 0.9 and 1.2 m^3/h its relative power demand is close to that of BT-4.

The results obtained indicate that the blade shape affects the power demand for unsteady mixing. Comparison of relative power demand for BT-4 and BT-6 implies that, just as in case of steady mixing, impellers with more blades are preferred allowing for dispersion of more gas. Compared results for BT-4 and BT-4E imply that the use of an ellipsoidal blade allows obtaining higher mixing power than the ellipsoidal open blade. In case of relative power RPD, the results are similar. In case of all impellers, RPD values are higher than for Rushton turbine for which RPD was about 0.42 (Woziwodzki and Broniarz-Press 2014). Considering RPD, the recommended impeller is the one with no flat blades and BT-6 is preferred for higher speeds ($Fl_g < 0.07$) and BT-4E in case of lower speeds ($Fl_g < 0.07$).

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References

Bakker A (2000) A new gas dispersion impeller with vertically asymmetric blades. In: The online CFM book. http://www.bakker.org.cfm

Kamieński J (2004) Mieszanie układów wielofazowych. WNT, Warszawa

Kamieński J, Wójtowicz R (2001) Power input for a vibromixer. Inż Chem Proc 22:603–608

Kamieński J, Wójtowicz R (2003) Dispersion of liquid–liquid systems in a mixer with a reciprocating agitator. Chem Eng Process 42:1007–1017

Karcz J, Cudak M, Szoplik J (2005) Stirring of a liquid in a stirred tank with an eccentrically located impeller. Chem Eng Sci 60:2369–2380

Komoda Y, Inoue Y, Hirata Y (2000) Mixing performance by reciprocating disk in cylindrical vessel. J Chem Eng Jpn 33:879–885

Komoda Y, Inoue Y, Hirata Y (2001) Characteristics of turbulent flow induced by reciprocating disk in cylindrical vessel. J Chem Eng Jpn 34:929–935

Kordas M, Story G, Konopacki M et al (2013) Study of mixing time in a liquid vessel with rotating and reciprocating agitator. Ind Eng Chem Res 52:13818–13828

Masiuk S (1999) Power consumption measurements in a liquid vessel that is mixed using a vibratory agitator. Chem Eng J 75:161–165

Masiuk S (2000) Mixing time for a reciprocating plate agitator with flapping blades. Chem Eng J 79:23–30

Masiuk S (2001) Dissolution of solid body in a tubular reactor with reciprocating plate agitator. Chem Eng J 83:139–144

Masiuk S, Rakoczy R (2007) Power consumption, mixing time, heat and mass transfer measurements for liquid vessels that are mixed using reciprocating multiplates agitators. Chem Eng Process 46:89–98
Masiuk S, Rakoczy R, Kordas M (2008) Comparison density of maximal energy for mixing process using the same agitator in rotational and reciprocating movements. Chem Eng Process 47:1252–1260
Middleton JC, Smith JM (2004) Gas-liquid mixing in turbulent systems. In: Paul EL, Atiemo-Obeng V, Kresta SM (eds) Handbook of industrial mixing. Science and practice. Wiley, Hoboken, pp 585–635
Montante G, Bakker A, Paglianti A et al (2006) Effect of the shaft eccentricity on the hydrodynamics of unbaffled stirred tanks. Chem Eng Sci 61:2807–2814
Morison JR (1953) The force distribution exerted by surface waves on piles. University of California, Institute of Engineering Research, Berkeley
Ng KC, Ng EYK (2013) Laminar mixing performances of baffling, shaft eccentricity and unsteady mixing in a cylindrical vessel. Chem Eng Sci 104:960–974
Ni X, Gao S (1996) Scale-up correlation for mass transfer coefficients in pulsed baffled reactors. Chem Eng J Biochem Eng J 63:157–166
Wójtowicz R (2012) Wizualizacja procesu wytwarzania emulsji w mieszalniku z mieszadłem wykonującym ruch posuwisto-zwrotny. Inż Apar Chem 51:402–403
Woziwodzki S (2011) Unsteady mixing characteristics in a vessel with forward-reverse rotating impeller. Chem Eng Technol 34:767–774
Woziwodzki S (2017) Mieszanie nieustalone - analiza i wybrane zastosowania. Wydawnictwo Politechniki Poznańskiej, Poznań
Woziwodzki S, Broniarz-Press L (2014) Power characteristics of unsteadily rotating Rushton turbine in aerated vessel. Tech Trans 2–Ch:155–164
Woziwodzki S, Jędrzejczak Ł (2011) Effect of eccentricity on laminar mixing in vessel stirred by double turbine impellers. Chem Eng Res Des 89:2268–2278
Woziwodzki S, Broniarz-Press L, Ochowiak M (2010) Effect of eccentricity on transitional mixing in vessel equipped with turbine impellers. Chem Eng Res Des 88:1607–1614
Yoshida M, Yamagiwa K, Ohkawa A et al (1999) Torque of drive shaft with unsteadily rotating impellers in an unbaffled aerated agitation vessel. Mater Technol 17:19–31
Yoshida M, Ito A, Yamagiwa K et al (2001a) Power characteristics of unsteadily forward-reverse rotating impellers in an unbaffled aerated agitated vessel. J Chem Technol Biotechnol 76: 383–392
Yoshida M, Yamagiwa K, Ito A et al (2001b) Flow and mass transfer in aerated viscous Newtonian liquids in an unbaffled agitated vessel having alternating forward-reverse rotating impellers. J Chem Technol Biotechnol 76:1185–1193
Yoshida M, Hiura T, Yamagiwa K et al (2008) Liquid flow in impeller region of an unbaffled agitated vessel with an angularly oscillating impeller. Can J Chem Eng 86:160–167. https://doi.org/10.1002/cjce.20028
Yoshida M, Nagai Y, Yamagiwa K et al (2009) Turbulent and laminar mixings in an unbaffled agitated vessel with an unsteadily angularly oscillating impeller. Ind Eng Chem Res 48: 1665–1672
Yoshida M, Wakura Y, Yamagiwa K et al (2010) Liquid flow circulating within an unbaffled vessel agitated with an unsteady forward-reverse rotating impeller. J Chem Technol Biotechnol 85:1017–1022