"EFFECT OF ANTERIOR AND POSTERIOR ANGLE ON MASS TRANSFER RATES WITH 'V' RING TURBULENCE PROMOTER IN CONDUITS"

Ratna Srinath Rao B[1*], K SudhaRani[2], N Chandra Sekhar[3], Ajmeera Ramesh[4]

Article History: **Received: 15/06/2018** **Accepted: 15/09/2018**

Abstract
Intensification of transport processes is carried out with V - ring as turbulence promoter in circular conduit. Diffusion controlled redox couple (Ferri Cyanide-Ferro Cyanide) reaction system has been chosen for the present study. The mass transfer coefficients were evaluated from the measured limiting currents and from the concentrations of the reactant species. Mass transfer coefficient was computed from measured limiting currents and the study continued in terms of geometric parameters such as wire diameter (d_w), anterior angle (α_1), posterior angle (α_2) and velocity (V). Mass transfer coefficients increased with an increase in wire diameter of the wire of the V-ring, and decreased with an increase in anterior angle (α_1), and decreased with increasing posterior angle (α_2). A maximum augmentation of 6.5 fold was achieved for the promoter with wire diameter (d_w=0.00326 m), anterior angle ($\alpha_1=30^0$), posterior angle ($\alpha_2=16^0$) for V - ring promoter. Maximum performance index was obtained for the best promoter with the geometric parameters: 0.00326 m wire diameter, 30^0 anterior angle, 16^0 posterior angle.

Keywords: Mass transfer coefficient, posterior angle, anterior angle

[1*,3,4]Dept. of PE & PCE, JNTUK, Kakinada,
[2] Dept. of Chemical Engineering, Andhra University

***Corresponding Author:** Ratna Srinath Rao B
*Dept. of PE & PCE, JNTUK, Kakinada, Email: srinathraobr@gmail.com

DOI: - DOI: 10.17628/ecb.2018.7.357-364

INTRODUCTION

Intensification of transport processes has been the endeavor of process engineers either for the reduction in equipment size or to enhance throughputs. Process intensification is also an excellent tool to mitigate de-bottlenecking in heat and mass transfer operations. Reduction in equipment size has an advantage of lower fixed costs for a particular duty with consequent lower cost cutting per unit product. In pursuit of these objectives a good number of techniques have been under investigation while some are commercially exploited. The process intensification is also called process augmentation or enhancement technique. The techniques under consideration were broadly classified as passive and active technique. Active techniques employ additional power source while passive techniques do not demand any. Devices such as surface vibrators (Hosseinian et al., 2017), pulsators (Wernik et al., 2015) application of sonicators and several rotating devices fall under active categories. A major disadvantage is additional mechanics and power sources are to be integrated with system.

Passive augmentation devices do not demand additional power for rotating fluid/surface. They don't need any rotating elements in the equipment. Such devices are simple based on the geometry of the promoters. One can control the enhancements by changes in the design. Several kinds of passive augmentation systems are under investigation with partial success depending upon the type of system under consideration and the processes. These passive systems are classified as surface alterations, displaced promoters, fluidizing systems, multiple flow systems, vortex generators, tangential and snail entry. Out of all, displaced promoters have advantages of easy design, installation and operations. They are classified as axially displaced promoters, asymmetric promoters. Axially displaced promoters range from axially displaced annular rod to geometries like short length twisted tape (Eiamsa-ard et al., 2009), v-cut twisted tape (Saravanan et al., 2016) spheres , string of spheres (Rohinikumar et al., 2016), fins (Mao-Yu-Wen and Ching-Yenho., 2009), are placed across the flow were also extensively found in literature. Flow through ducts and arched channels (Niu et al., 2002), were also found. The investigations on co - axially placed promoters are many and studies like twisted tapes (Paisarn ., 2006), helical tapes wound on a rod (Sujatha et al., 2003), spiral coils (Rajendra et al.,2004), discs (Murali., 2008), orifices (Sujatha .,2003), circular rings placed on a rod (Goplakrishna., 2001), vane assembly (Penta., 2015),conical springs (Hakan .,et.al., 2013), vortex rings (Promovonge et al., 2013) , V ring (Promovonge et al., 2017)were found in literature. Several heat and mass transfer operations warrant augmentative devices for effective operations. Some operations need augmentation such as heat exchangers with and without phase change, they are well tested and brought to industrial scale practice. The list is long and up to the imaginative capacity of the researchers. To achieve higher augmentations, different methods were employed to improve heat and mass transfer rates. The quest for a best promoter which augments better at reasonably low energy loss was found to continue in literature.

Concentrically placed rings produce turbulence with drag created behind the rings propagate turbulence and affects boundary layer thickness at the transfer surface, leading to higher mass transfer rates. Modification of concentric rings resulted in double V-ring promoters. Enhanced drag is envisaged behind double V- rings placed across the flow in circular conduits. The drag generated by these rings offer relatively lower friction losses for a unit change of mass transfer. The V- ring promoter generate vortices behind the ring and affect mass transfer at the wall. It is envisaged to test effect of V- ring angles namely anterior angle (α_1), posterior angle (α_2), and diameter of the wire of V ring (d_w). All the parameters showed significant effect on mass transfer in homogeneous flow. The ranges of variables studied are presented in Table 1.1. It is found that mass transfer coefficient (k_L) is increased with wire diameter (d_w).

Table 1.1: Range of variables covered in the present study

Variable	Minimum	Maximum
Diameter of the wire (d_w), m	0.00163	0.00326
Anterior angle (α_1), degree	30^0	60^0
Posterior angle (α_2), degree	16^0	76^0
Reynolds number, Re	3171	29540
Schmidt number, Sc	846	1116

Experimental Setup:

Electrolyte was pumped & recycled through the circular conduit. The electrolyte consisted of potassium ferricynaide (0.01N) and potassium ferrocynaide (0.01N) as redox couple along with sodium hydroxide (0.5N). The electrolyte was circulated through conduit with V ring promoter assembly and limiting current data on the reduction of ferricyanide ion was measured. The reaction which takes place in the system is the cathodic reduction of ferricyanide ion at the reacting electrode as:

$$[Fe(CN)_6]^{-3} + e^- \text{--------} [Fe(CN)_6]^{-4} \rightarrow 1$$

Mass transfer coefficients are computed from the measured limiting currents by the following equation:

$$k_L = \frac{i_L}{nFA_eC_o} \rightarrow 2$$

Where , A_e is Area of electrode, c_o is concentration of electrolyte, F is faraday's constant , i_L is limiting current, k_L is mass transfer coefficient, n is number of moles transferred.

The conduit consists of three parts, entrance calming section, test section and exit calming section. The entrance calming section and exit calming section were made of copper tube of 0.046m ID and length of the entrance calming section was 40D. The exit calming section was also made of copper tube of length 0.7m and diameter of 0.046m. To an extent of 0.1 m capillary tube were used to fill the entrance calming section to damp the flow fluctuations to facilitate steady flow. The test section was made of poly methyl methacrylate (perpex) tube of length 68 cm with 0.046m ID and 18 point electrodes were flush on the inner surface of the outer tube of the test section with equal spacing of 3 cm. Point electrodes made up of copper were machined to equal size.

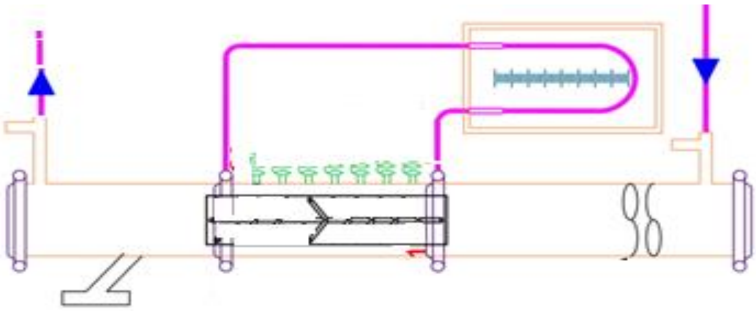

Fig. 1: Experimental Setup

V ring Promoter:

V- Ring promoters were made with Copper metallic wire of different wire diameter 0.00326m, 0.00258m, 0.00163m. Copper wire was bent in to V shape. V- Shape was made with different anterior angle (α_1) viz. 30^0, 40^0, and 60^0. Two V shaped rings with same anterior angle, same wire diameter were taken and mounted on two brass rods on either side of brass rod to form a sharp V-ring junction with an angle called as posterior angle(α_2) shown. The diameter of the brass rod was same with respect to the wire diameter of V shape ring. With different combinations of anterior angle, wire diameter, posterior angle promoters were designed. For an anterior angle $\alpha_1=30^0$, three posterior angles combinations are $\alpha_2= 30^0, 20^0, 16^0$, similarly for $\alpha_1=40^0$, $\alpha_2= 48^0, 36^0, 24^0$ and for $\alpha_1=60^0$, $\alpha_2= 76^0, 60^0, 42^0$.

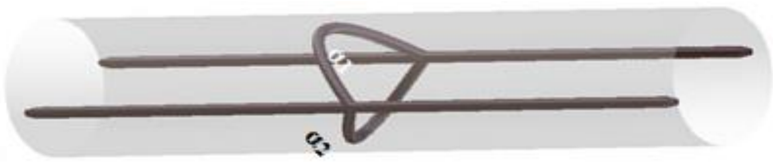

Fig 2: V ring inside test section indicating anterior and posterior angle.

RESULTS & DISCUSSION

Augmentation capacity:

The effectiveness of a specific promoter element is adjudged by the enhancement one gets in the transfer coefficient with respect to dynamic parameter of the fluid. The investigation is aimed at achieving higher augmentation over conduits without promoter. A graph is drawn as mass transfer coefficient versus velocity and shown in fig 3. The figure contains plots for the best augmenting set (A) and least augmenting set (B) within the range of variables covered in the present study without any promoter placed inside the test section. Augmentation is due to presence of a V-ring promoter. It varies 3.09 to 6.12 folds at a velocity of 0.0631 m/s while that at higher velocity of 0.52 m/s is reduced to 3.7 to 2.4 fold. The augmentation obtained is reasonably high, hence further experimentation was conducted with varying geometric parameters of angle (α_1) that is angle of the promoter on the anterior side of promoter while the angle (α_2) is the posterior side of the promoter.

Effect of variation of anterior angle, (α_1):

A graph is drawn as mass transfer coefficient (k_L) versus velocity (V) and shown in fig 4. The figure depicts the effect of anterior angle (α_1). As the angle α_1 increased from 30^0 to 60^0, mass transfer coefficient values are decreased. It may be due to the decreased side length of the V- ring which is responsible for guiding the flow. Lower the angle greater the length of the V-ring which induces flow in the direction of wall, hence greater the turbulence in buffer zone which in turn responsible for thinning of laminar sub layer and thereby enhancement of mass transfer. A maximum augmentation of 5.5 to 3.7 fold was achieved for maximum augmenting set within the range of variables covered in the study.

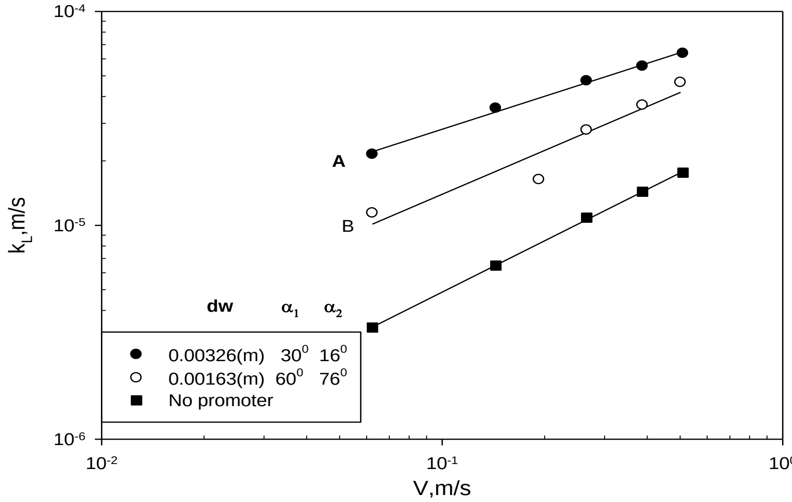

Fig 3: Augmentation capacity of V-ring

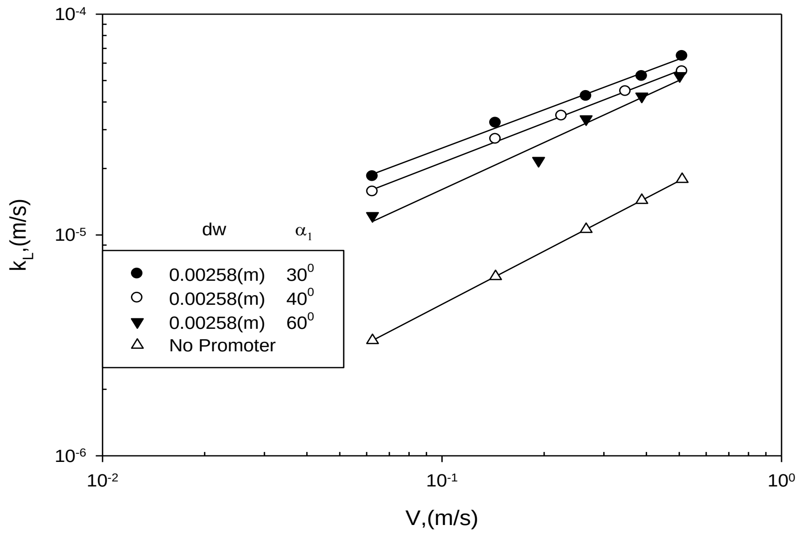

Fig. 4: Effect of varation of anterior angle(α_1)

Effect of variation of posterior angle, (α_2):

A graph is drawn as mass transfer coefficient (k_L) versus velocity (V) with posterior angle α_2 as parameter and shown as fig.5. Posterior angle α_2 is varied as 16^0, 20^0 and 30^0. At higher values of angle α_2, the tip of the V- ring approaches the wall, fair augmentations are resulted. As the value of α_2 decreases, the tip of the V- ring falls in to the turbulent core hence generating wakes which in turn enhances turbulence near the wall thereby giving higher augmentation values. The maximum augmentation is recorded for angle 16^0 while minimum at 20^0. An augmentation of 5.5 to 3.5 fold was achieved as the velocity varies from 0.063 m/s to 0.52 m/s.

Effect of variation of wire diameter (d_W):

Wire diameter of the double V ring promoter has influence on the mass transfer coefficient (k_L) values as it forms an obstruction to the flow causing resistance to flow, thereby enhancing the contact area of the promoter to fluid which influences the turbulence by forming wakes behind the V- ring. The flow fields generated influences the velocity profile. The net effect of the promoter is thinning of mass transfer laminar sublayer, resulting in enhancement of k_L values. Fig. 6 is a graph which depicts the effect of wire diameter of the promoter. It is a graph of mass transfer coefficient (k_L) versus velocity (V). k_L values are increasing with an increase in wire diameter d_w. Augmentation varies from 3.6 to 6.12 folds for best promoter (i.e. for wire diameter 0.00326(m)).

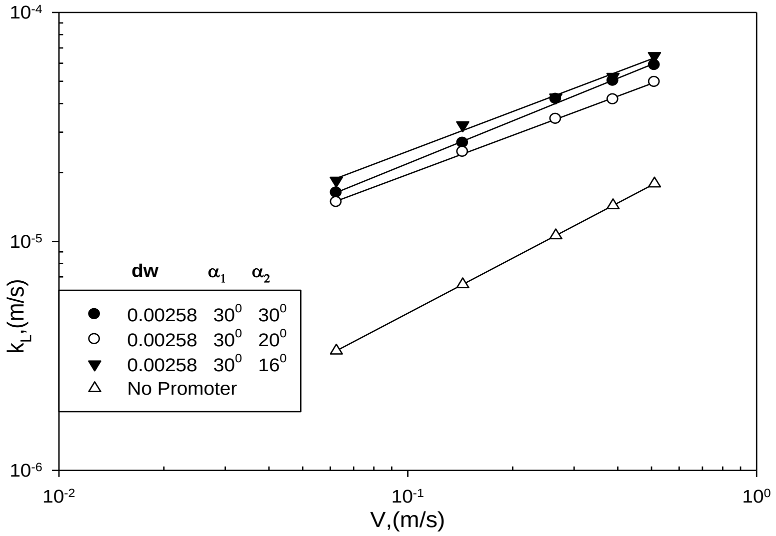

Fig. 5: Effect of varation of posterior angle (α_2)

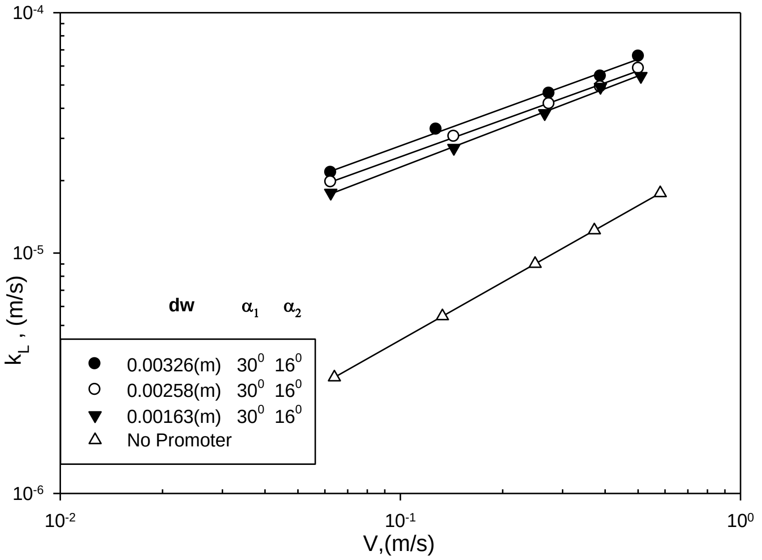

Fig. 6: Effect of variation of wire diameter

Energy factor:

Energy factor is defined as the ratio of pressure energy lost with promoter to with no promoter in the conduit and is indicated by E/E_0.

$$\frac{E}{E_0} = \frac{\left(\Delta p / L\right)}{\left(\Delta p_o / L\right)} \quad \rightarrow 3$$

Fig. 7 depicts the energy changes with Reynolds number for two sets of data which augments the best and the least in the present study. The graph reveals the energy data values decreasing with Reynolds number. But in the case of best augmenting set the energy factor decreases to minimum followed by an increase from which one can conclude that operating at minimum energy factor values are desirable. Energy factor varies from 33 to 12 fold for best augmenting promoter while tapered off from 11 to 6.8 fold for least augmenting promoter assembly.

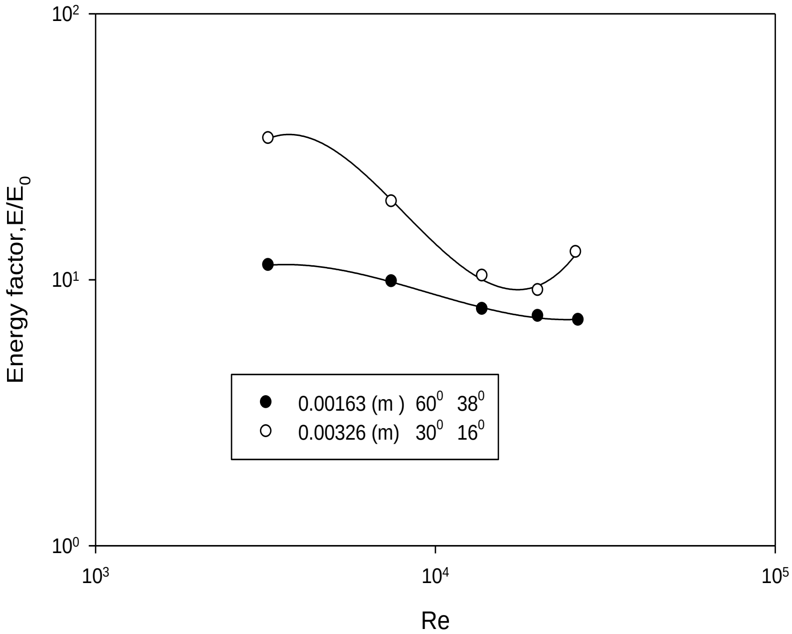

Fig. 7: Energy factor

Performance of V ring:

Performance factor (η) is the ratio of augmentation factor (k_L/k_{Lo}) to the energy factor (E/E_o) and is given by the following expression

$$\eta = \frac{k_L/k_{Lo}}{E/E_o} = \frac{k_L/k_{Lo}}{\Delta p/\Delta p_o} \qquad \rightarrow 4$$

A plot is drawn for performance factor (η) versus Reynolds number and shown in fig.8 Efficiency of the promoter under study could be judged from graph of η versus Reynolds number. Efficiency is increased with an increase of Reynolds number up to 18000 beyond that it decreased. The promoter producing maximum turbulence augmented better and efficiencies increased steeply indicating higher augmentation at lower flow rates.

Comparison:

A graph is drawn as efficiency of the promoter versus Reynolds number and shown in fig.9. The figure indicates that the plots of data pertaining to full length coils, full length twisted tape wound on a rod in circular conduits along with present work. The figure also contains the data of entry region coil, entry region twisted tape, entry region vane assembly promoters. The figure reveals that the present study is efficient than any other promoters presented in the graph particularly at higher Reynolds numbers.

Conclusion:

In all the cases studied in the present work it is observed that the augmentation of limiting current over conduit with no promoter ranged from 2.4 to 6.5 fold. The effect of anterior angle of V ring promoter showed increased in augmentation with increase in anterior angle and mass transfer coefficient (k_L) is increasing with increase in wire diameter of V-ring promoter. As posterior angle (α_2) value decreased, mass transfer coefficient values increased to a maximum followed by decrease. Efficiency is increased to a peak value followed by a decrease.

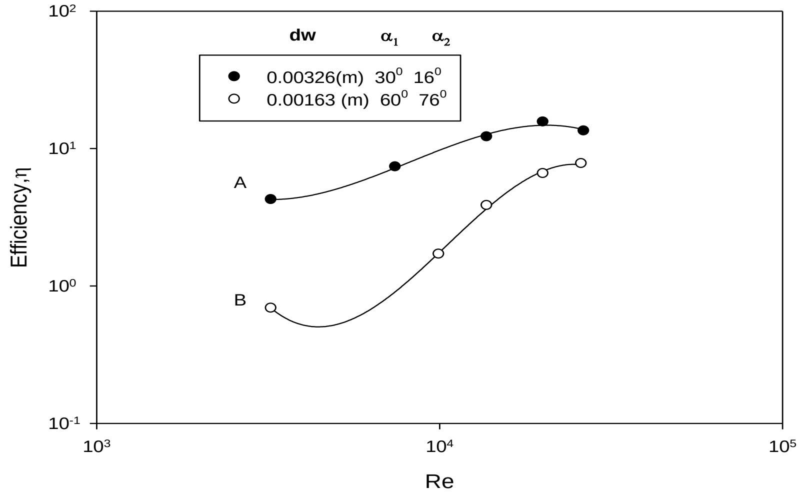

Fig. 8: Efficiency graph

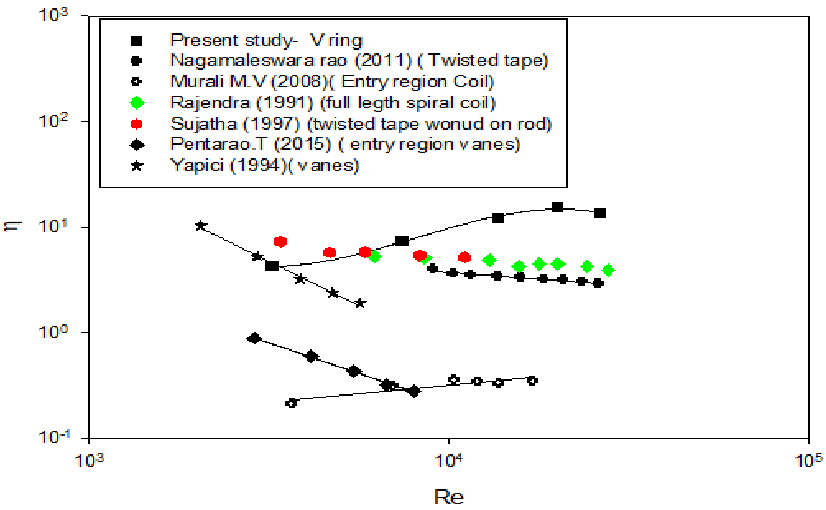

Fig. 9: Comparison graph - Efficiency

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