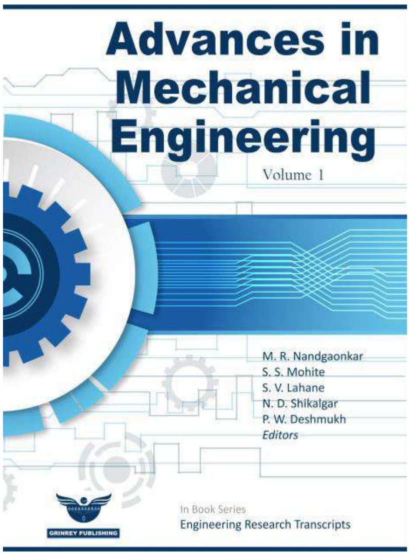

Experimental Study on Heat Transfer Enhancement and Pumping Loss In R407c Evaporator Using Twisted Tape

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Abstract
An experimental study on heat transfer enhancement and pumping loss is done during evaporation of R407C in horizontal 2 m long copper tube Evaporator. Plain tube and plain tube with turbulent promoters are considered for investigation. Experimentation is carried on the plane tube and plane tube with twisted tapes. Operating conditions: refrigerant mass flux, G-100 – 350 kg $m^{-2}s^{-1}$, heat Flux, q-1.4 – 9.1 kW m^{-2}, temperature range: -14 to 10.9 ^{0}C, pressure range (absolute): 3.5 -8 bar and vapor quality, x- 0.05 - 0.95.Three twisted tapes are used as turbulent promoters of twist ratios 8, 10 and 12. Study reveal that heat transfer enhancement depends on geometry of twisted tape and operating conditions. Twisted tape with twist ratio, y = 12 shows maximum heat transfer at all operating conditions with 56.51% maximum average increase in heat transfer coefficient. With increasing operating conditions of heat flux, mass flux and pressure, pumping loss increases. Twisted tape with twist ratio, y = 12 is giving minimum percentage increase of pumping loss from 2.57% to 5.20% over plain tube.

1. Introduction

Swirl The rate of heat performance is accelerated by the swirl flow created by the turbulent promoter. Due to the turbulence promoter, M. Cumo et al. [1] discovered a 200% increase in heat transfer at the dry out point in the Evaporator of Feron 12. [2,3,4] have conducted an experimental investigation on the use of twisted tapes to improve heat transfer during the evaporation of Feron 12. According to their research, the twist ratio and test conditions have an impact on heat transfer enrichment. Mark.A.Kedzierski et al.[5] attribute the drop in Nusselt number with increasing vapour quality to twisted tape produced a partial dry out of the inner tube surface.

In the condensation of R22, the research of Ramakant Shrivastav et al [6] discovered when twisted tape with a twist ratio of 6 was compared to twisted tape with a twist ratio of 15 and 9, the heat transmission performance improved by 25%. However, M.A. Akhavan et al. [7-8] discovered that using twisted tapes with twist ratios of 15, 12, 9, 6, and with coiled wire inserts of 13, 10, 8, and 5 mm resulted in a larger pumping power penalty at the charge of improvement in heat transmission. Nano fluid with Coiled wire inserts flow were employed by M. Saeedinia et al. [9] to demonstrate similar types of increases in Nano particle concentration with increasing pressure drop and heat transfer.

In areas where the vapour quality is high, twisted tapes are profitable. Taye Steven Mogaji and others [10]. Because they provide a vast heat transfer area, spongey inserts significantly improve heat transfer. Mao-Yu Wen and others [11] For improving heat transfer, annular and intermittent flow patterns are more efficient. [12] Maziar Shafaee et al.

Coiled tubes have been employed by [13,14,15] to improve heat transfer. In areas with high vapour quality, the curvature radius or coiled tube diameter has a larger effect on the heat transfer performance Ahmad Reza Salimpour and others [13].

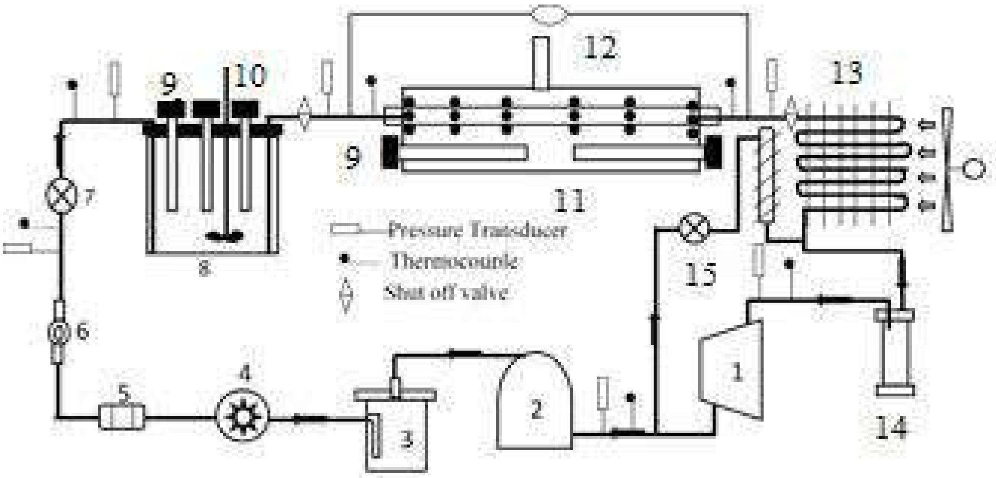
Excellent thermal performances have made the R22, a leader refrigerant in refrigerant industries. But due its high ozone depletion and global warming potential, it has been banned to use after 2020. Refrigeration industries demanding new refrigerants as a substitute to R22, having zero ODP and minimum global warming potential. Many refrigerants such as R407C, R 410A, R-290, R-134a,etc.are promising solution to R22.However,R134a produce acid and poisonous products when get decompose due to sunlight in troposphere, which can be a worst situation than global warming and ozone depletion. Shailendra Kasera et al. [16].On the other side R-290 has a safety issues in handling. Thermo-physical properties of R407C are closer to R22, compare to other substitute and hence shows thermal performance near to R22. It can be used in the existing refrigeration systems handling R-22 as a best retrofit to R22. C. Aprea al. [17], suggested R407C as possible substitute to R22. [18,19,20] have compared the performance of R407C with R22 experimentally and found that the thermal performance of R407 C is slightly lagging the performance of R22. As per reports of United Nations Environment Programme (UNEP) [21] & [22], R-407C is a best transitional refrigerant with little modification in the existing system using R-22 to use R-407C as a substitute. Juan Garcia et al.[23] tested effect of diameter , quality, heat flux, mass flux and pressure on two phase pressure drop of R407C. Recently, P HorakM et al. [24] worked on evaporation R407C in vertical smooth evaporation tube and stated that convective boiling suppressed heat transfer and nucleate boiling dominant heat transfer at low flux of 9 kgm-2s-1.

Thus from different investigations on R407C, it can be concluded that R407C is a promising substitute to R 22. However, the thermal performance of R407 C should be enhanced, using heat transfer enhancement techniques. Hence in the present work, twisted tapes are used to investigate heat transfer enhancement during flow boiling of R407C in horizontal evaporator. On the other side, pumping loss due to twisted tapes are to be checked against heat transfer enhancement. This will help to understand the benefits of heat transfer enhancement technique. Hence in the current investigation, experimental study on heat transfer enhancement and pumping loss in R407C Evaporator is carried out using twisted tape as a turbulent promoters.

2. Experimentation

Figure 1 shows layout diagram of experimental test facility. Experimental test facilities consist of refrigerant flow loop with flow meter, pre-evaporator, test- evaporator, after-evaporator, accumulator, compressor, bypass valve, condenser, receiver, sight glass and manual expansion valve as shown in figure 1.

Pre-evaporator adjusts the quality of refrigerant as per requirement at entry of test-evaporator. Solid state relay with PID controller is used to control heat input precisely in the pre-evaporator. Test-evaporator is a long cylindrical stainless-steel pipe with copper test tube passing through it. Test-evaporator is filled with water-glycol solution. Two heating rods, 0.9 m each in length are fitted into the test evaporator, parallel to copper test tube as shown in figure 1. Heat input in test-evaporator is controlled through solid state relay controller. Four thermocouples are brazed in a group on the outer periphery of test tube, with each thermocouple separated by 90^0 from each other as shown in figure 2. There are six such groups of thermocouples brazed on the outer surface of test tube, equidistant from each other. On downstream side of test-evaporator, after-evaporator is fitted in the refrigerant line to adjust the superheat of refrigerant at inlet to compressor.



1-Compressor, 2-Condenser, 3-Receiver, 4-Flow meter,5- Drier,6-Sight Glass,7-Manual Expansion Valve,8- Pre- Evaporator,9-Heater,10-Stirrer,11-TestEvaporator, 12-Differential Pressure Transducer, 13-By Pass Valve, 14-Accumulator, 15- By Pass Valve

Fig. 1. Experimental setup.

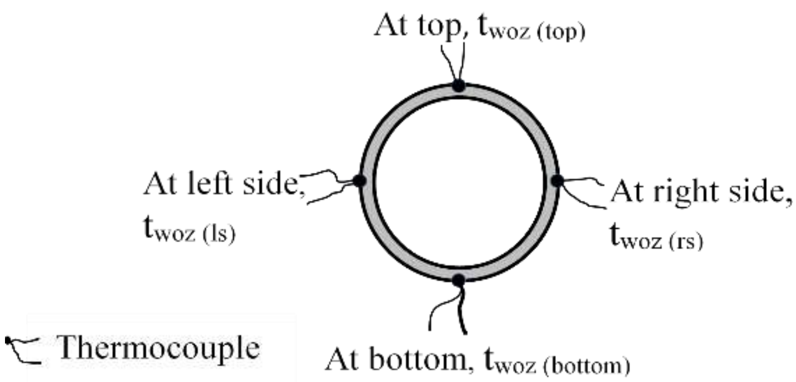


Fig. 2. Test section tube with thermocouples

T -type thermocouples and absolute pressure transducers (Piezo-resistive) are used to measure pressure and temperature of refrigerant. Pressure drop across the test-evaporator to calculate pumping loss in the test -evaporator is measured by differential pressure transducer (Piezo-resistive type). For refrigerant flow measurement, oval gear type flow meter is used. Table I shows instrument's accuracy with range.

Table 1: Accuracy with range of instruments

Variable	**Instrument**	**Accuracy**	**Range**
Temperature	T-type thermocouple	± 0.375^{0}C	-40 ^oC to 150 ^oC
Pressure	Piezo Resistive	± 0.25 % FS	0 to 20 bar (Abs)
Differential Pressure	Piezo Resistive	± 0.1 % of URL	0 to 0.3 Bar
Mass flow rate	Oval gear- Positive displacement	± 0.15 %FSD	20 to 300LPH

Table 2: Specification of Twisted Tapes

	Material	**Thickness (t) mm**	**Pitch (H) mm**	**Width of twisted tape ≈ inner diameter of tube in mm (d)**	**Twist ratio, y = H/d**
Twisted Tape I	Copper	0.25	105	13	8
Twisted Tape II	Copper	0.25	132	13	10
Twisted Tape III	Copper	0.25	156	13	12

Table 3: Operating Parameters with operating range

Sr.No.	Operating parameters	Range
1.	Mass flux, G ($kgm^{-2}s^{-1}$)	100 - 350
2.	Heat Flux, q (kWm^{-2})	1.4 - 9.5
3.	Evaporating pressure in test section (bar)	3.5 - 8
4.	Evaporating temperature in test section- Ts (^0C)	-14 to 10.9
5.	Average vapor quality in test section, *x*	0.05 - 0.95

Figure 3 shows twisted tapes used in the present experimentation. Table 2 shows geometrical specifications of twisted tape. Table 3 shows operating parameters and their range.

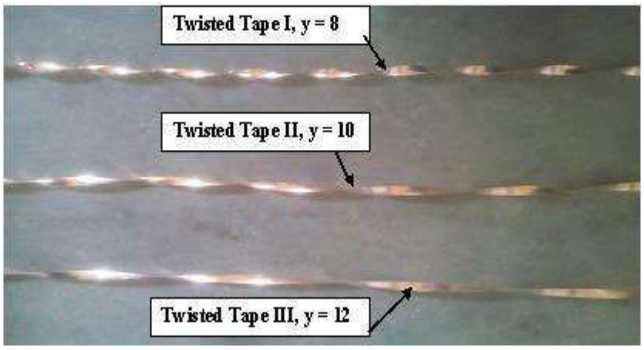


Fig. 3. Twisted tapes used for experimentation

Data reduction

Experimental heat transfer coefficient in test-evaporator is calculated, using equation 1.

$$\mathbf{h = qts/(twi\text{-}tsat)} \qquad \mathbf{(1)}$$

qts - heat flux (kWm^{-2}) on the test section tube, calculated as,

$$\mathbf{qts} = \frac{\mathbf{Qts}}{\mathbf{As}} \qquad (2)$$

Where,

$$Qts = Qh - QL \qquad \text{(kW)} \qquad (3)$$

Qts is net heat (kW) given to test section tube, Qh - total heat from test-evaporator heaters, QL - heat loss to surrounding, estimated from heat leakage calibration curve or heat loss equation .

t_{wi} in equation (1) is calculated using equation (4).

$$\boldsymbol{twi = two - \left(\frac{Q}{2\prod LK}\right) * ln\left(\frac{do}{di}\right)} \qquad \textbf{(4)}$$

Average outside surface temperature of test–evaporator tube, $t_{wo,}$ is obtained through equation (5).

$$\boldsymbol{two = \frac{twoz1+twoz2+\cdots twoz16}{16}} \qquad \textbf{(5)}$$

Where, t_{woz1}, t_{woz2}, … … … … t_{woz6} are the average outside surface temperatures of test-section tube, measured at six locations z1, z2,….z6 on the copper tube and each is estimated as

Saturation temperature, $t_{sat,}$ corresponding to evaporating pressure at inlet to test section tube, in equation 1, is obtained from Refprop 7.0

Vapor quality is considered as an average of entry and exist vapor qualities of test- evaporator, using equation (7).

$$\boldsymbol{Xavg = \frac{Xin+Xout}{2}} \qquad \textbf{(7)}$$

xin & $xout$ are void fractions (vapor qualities) at entry and exist of test section**.**

Uncertainty in measurement of heat input, heat flux, mass flux and heat transfer coefficient is calculated using Robert J Moffat [25] method. If 'R' is the result and is a function of independent variables x1, x2, x3…….then uncertainty in result, uR is calculated according to Robert J Moffat [25] as,

$$u_R = \sqrt{\left(\frac{\partial R}{\partial x_1}u_1\right)^2 + \left(\frac{\partial R}{\partial x_2}u_2\right)^2 + \cdots\left(\frac{\partial R}{\partial x_n}u_n\right)^2} \qquad \textbf{(8)}$$

Table 4: Operating sets

Operating Set	**Operating Conditions**		
	Pressure, P (bar)	**Heat flux, q (kWm^{-2})**	**Mass Flux, G (kgm^{-2}s^{-1})**
1	4	2	130
2	6	4	170
3	8	9	250

3. Results and Discussions

3.1 Heat transfer enhancement using twisted tapes

Figure 5, 6 and 7 show how twisted tapes I, II, and III improve heat transfer coefficients compared to a plain tube. It is noted that the heat transfer improvement caused by twisted tapes over a plain tube can be noticed up to 60% vapour quality for all the twisted tapes in the graphs After 70% vapour quality region twisted tapes have a slightly better heat transfer coefficient than plain tube. The component R32 which is highly volatile of the zeotropic mixture R407C evaporates extremely quickly in comparison to other components in the lower vapour quality area of 0.1 to 0.6. As a result, the zeotropic mixture R407C's vapour to liquid density ratio rises and two-phase flow quickens. This acceleration causes swirl in the two-phase flow in addition to flow.

Respectively, the heat transfer coefficients within the vapour quality range of 10 to 60% are improved by all these favourable environmental factors. After 70% vapour quality, two phase flow transforms into mist flow due to ongoing improvements in the vapour to liquid density ratio (i.e. flow acceleration) and swirl. Once more, after 70% vapour quality, local surface dry out happens as a result of twisted tapes. Therefore, after 60% vapour quality, the improvement in coefficient of heat transfer over plain tube caused by twisted tapes can be found to be small.

In comparison to other twisted tapes, it appears that twisted tape-III having twist ratio 12 exhibits the more heat transfer performance in Figure 4, 5 and 6. Table 5 presents quantitative analysis to comprehend the extent of the increase in heat transfer performance brought on by the use of twisted tapes opposed to a plain tube.

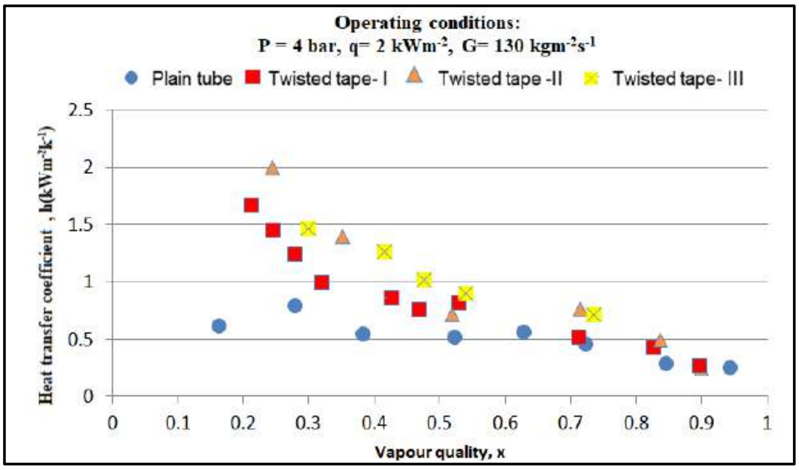


Fig. 4. Heat transfer coefficient enhancement due to twisted tape inserts I, II &III over plain tube at P = 5 b ar, q = 2 kWm^{-2}, G = 130 kgm^{-2}s^{-1}

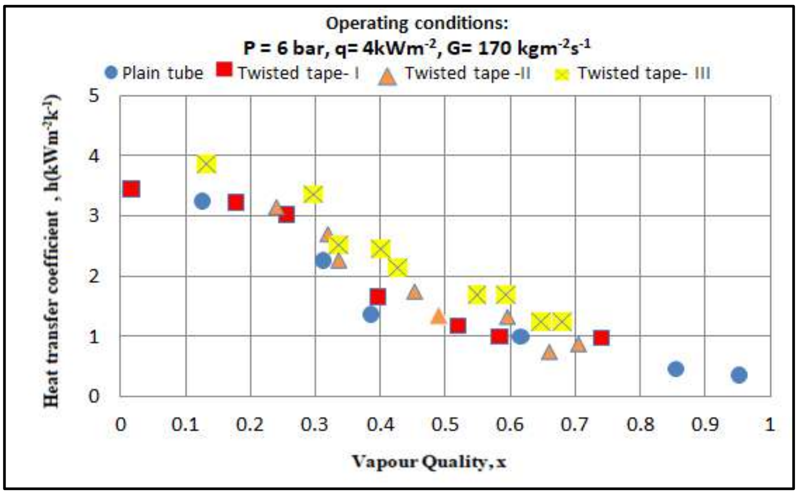


Fig. 5. Heat transfer coefficient enhancement due to twisted tape inserts I, II &III over plain tube at P= 6 bar, q = 4 kWm^{-2}, G = 180 kgm^{-2}s^{-1}

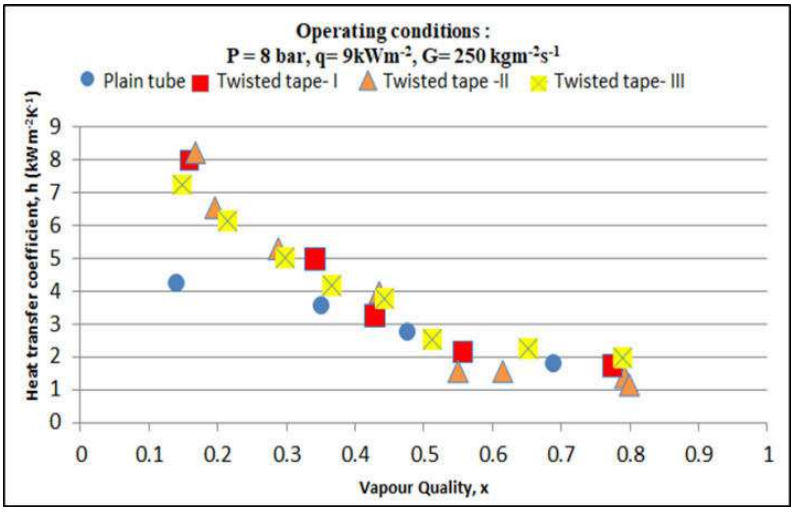


Fig. 6. Heat transfer coefficient enhancement due to twisted tape inserts I,II&III over plain tube at P = 8 bar, q = 9kWm^{-2} , G = 250 kgm^{-2}s^{-1}

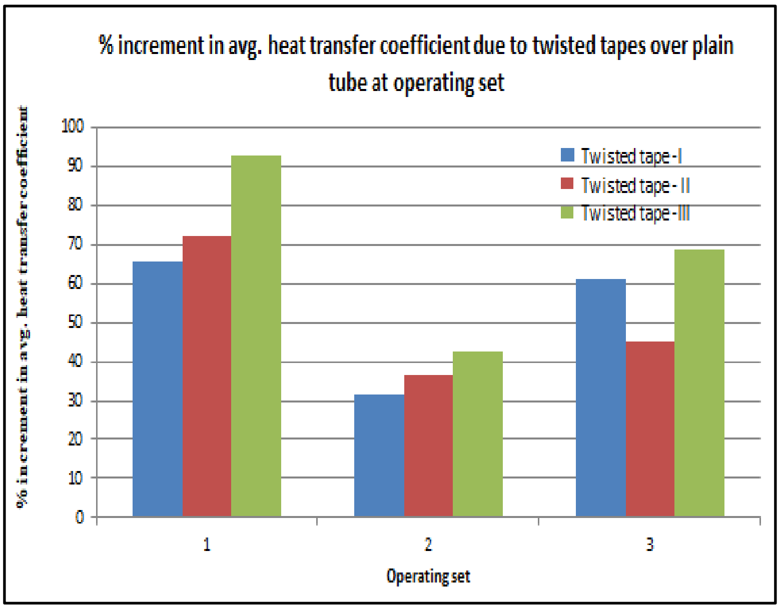


Fig. 7. Percentage increment in average heat transfer coefficient due to twisted tapes over plain tube at different operating conditions**.**

Table 5: Percentage increase of average heat transfer coefficient with twisted tape over plain tube

Set	Operating Conditions			Average Heat Transfer coefficient (havg), kWm^{-2}K^{-1}				% increase of havg over plain tube due to twisted tape inserts.		
	Psat bar	q kWm^{-2}	G Kgm-2s-1	Plain Tube	Twisted Tape I	Twisted Tape II	Twisted Tape III	Twisted Tape I	Twisted Tape II	Twisted Tape III
1	4	2	130	0.5230	0.8648	0.900282	1.00738	65.35	72.13	92.61
2	6	4	170	1.546	2.03257	2.1099	2.204881	31.47	36.47	42.61
3	8	8	250	2.47681	3.98404	3.593355	4.131831	60.85	45.08	68.47
Percentage of increase in heat transfer performance (average) with twisted tape over plain tube								52.55	51.22	67.88

Table VI indicates that all the twisted tapes of present investigation exhibits highest heat transfer performance with 63.20%, 71.33% and 84.25% increase of average heat transfer coefficient over plain tube at low operating condition (set1). As operating conditions increases the degradation in the performance of twisted tapes can be found in the table VI. Twisted tape-III shows maximum increase in average heat transfer coefficient of 56.51%. Figure 8 shows maximum % increment in average heat transfer coefficient at lower operating set '1'.

At operating set '1' (lower operating condition) and highest operating set '3', twisted tape of twist ratio 12 is performing better than other two twisted tapes. Increasing operating conditions means increasing pressure, mass flux and heat flux. These increased heat flux and mass flux conditions sustenance the heat transfer enhancement, but increased operating pressure condition suppressed the heat transfer enhancement. Thus, degradation in % increment of average heat transfer coefficient can be seen with increased operating set '2' and '3'.

3.2 Pumping power due to twisted tape

Turbulent promoters like twisted tapes and coiled wire inserts increases frictional pressure drop. As a consequences pumping power required to maintain the mass flow rate of refrigerant increases. Pumping power is calculated as a product of volume flow rate of refrigerant (m^3/sec) and pressure drop across test section tube (N/m^2).

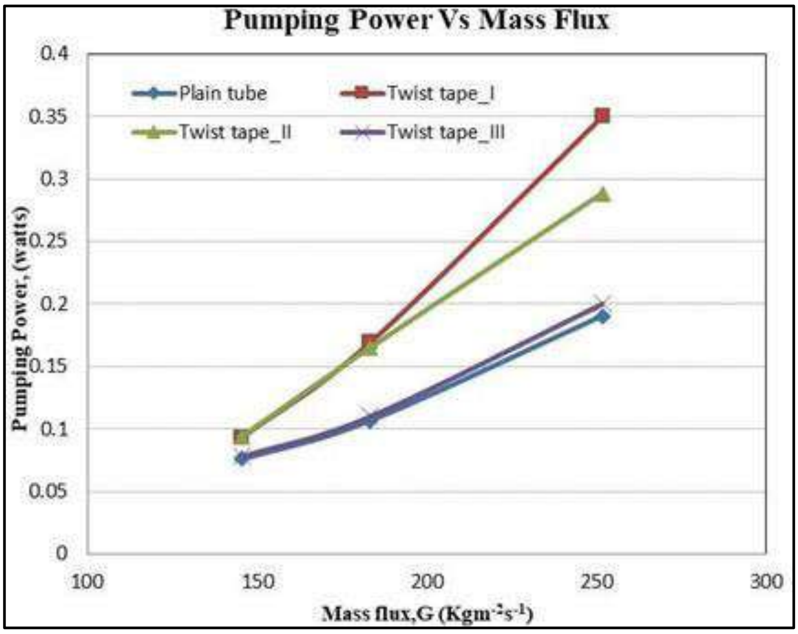


Fig. 8. Pumping power versus mass flux for plain tube and plain tube with twisted tapes.

Figure 8 shows variation of pumping power with mass flux for twisted tape-I, II&III. From figure 9, it can be seen that pumping power is increasing linearly with mass flux for all twisted tapes. twisted tape-III of twist ratio, y=12 is showing minimum rise in pumping power over plain tube. Twisted tapes, decreases open space across the flow. Thus, due to decrease in cross sectional area of flow, more resistance will be offer for refrigerant flow and hence more pumping power is required to maintain the mass flow rate of refrigerant. Again, swirl produce due to twisted tape also contributes in increasing frictional pressure drop. However, with increasing pitch or decreasing twist ratio of twisted tape, cross sectional area of the flow increases. This will help to reduce the frictional pressure drop and resistance to flow, resulting in to decrease in pumping power with increasing pitch. In addition to the mass flux and pitch of twisted tape, heat flux and saturation pressure also affect the pumping power with certain magnitude.

Selection of suitable turbulent promoters requires quantitative analysis of pumping loss due to turbulent promoters in heat transfer enhancement. Table 6 and table 7 provides the data for quantitative analysis of pumping loss by twisted tapes I, II and III.

Table 6 shows pumping power for plain tube and plain tube with twisted tape inserts at different operating parameters: saturation pressure, heat flux and mass flux. Table VIII shows percentage increase of pumping power due to twisted tape inserts in plain tube. General observation of table VII implies that pumping power increases with increasing operating condition . From twisted tape group, the range of increase of pumping power is minimum for twisted tape-III, which is 0.078 watt to 0.201 watt and is maximum for twisted tape-I from 0.093 watt to 0.349 watt. Out of the above twisted tapes, twisted tape-III with twist ratio, y = 12 is giving minimum increase of pumping power with increasing operating conditions. From table VIII, it can be observed that twisted tape-III is giving minimum percentage increase of pumping power from 2.57% to 5.20% over plain tube.

3.3 Heat transfer enhancement against pumping power

Using data of table 5 & 8, figure 10 shows % heat transfer enhancement due to twisted tapes against their increase in % pumping power at operating conditions or set 1,2 and 3. On the plot of figure 10, twisted tape-III (twist ratio 12) shows maximum vertical growth, means maximum heat transfer enhancement and minimum horizontal growth means minimum increment in pumping power. Twisted tape-I shows highest horizontal growth (i.e. highest pumping power) and lowest vertical growth (lowest heat transfer enhancement) on the plot of heat transfer enhancement against pumping power of figure 9.

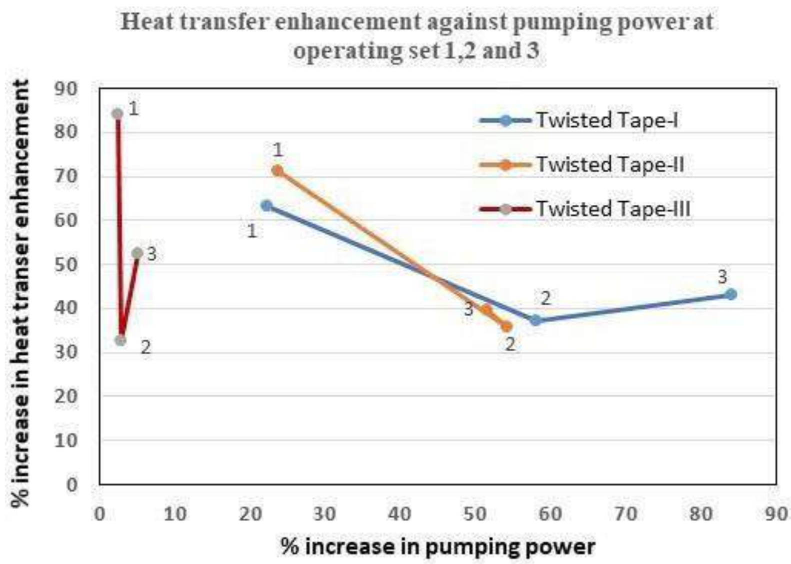


Fig. 9. Heat transfer enhancement against pumping power with respect to operating sets or conditions.

Thus, twisted tape III of twist ratio 12 shows maximum average 56.51% of heat transfer enhancement over a plain tube with minimum percentage increase of pumping power from 2.57% to 5.20% over plain tube among all the twisted tapes used in the present investigation. This seems that twisted tape -III of twist ratio 12 is found to be most suitable turbulent promoters for the heat transfer enhancement for the operating conditions of present investigation. Again, it seems that pumping power increases with increasing operating conditions for plain tube and plain tube with twisted tapes.

Table 6: Pumping power in Plain tube and Plain tube with inserts at differnt operating conditions.

Operating set	Operating conditions			Pumping Power in Test-Evaporator (watts)			
	Psat (bar)	Q (kW/m^2)	G (Kg/m^2s^1)	Plain tube	Twisted tape-I	Twisted tape-II	Twisted tape- III
1	5	2.185	145.7	0.076	0.093	0.094	0.078
2	6	4.17	183.32	0.106	0.169	0.164	0.110
3	7	9.1	251.7	0.190	0.349	0.288	0.201

Table 7: Percentage increase of Pumping power due to inserts in plain tube over pumping power in plain tube.

Mass flux, G $kgm^{-2}s^{-1}$	Percentage increase of pumping power for plain tube with inserts with respect to plain tube (%)		
	Twisted tape-I	Twisted tape-II	Twisted tape- III
145.7	22.40	23.70	2.57
183.32	58.23	54.24	2.99
251.7	84.02	51.62	5.20

4. Conclusion

Through results and discussion, following conclusions can be drawn.

- All twisted tapes are effective in lower vapor quality region of 10 to 60% only.
- Effectiveness of twisted tapes depends on operating conditions, vapor quality region, geometry of twisted tapes and pumping loss.
- In the current investigation twisted tape–III of twist ratio12 shows best heat transfer performance with 56.51% increase in average heat transfer coefficient and minimum pumping loss from 2.57% to 5.20%.
- For any turbulent promoter, its higher vertical performance growth and lower horizontal performance growth on heat transfer-pumping power plot, indicates its suitability as a turbulent promoters for the heat transfer enhancement within the given operating range.

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