Effects of Velocity Profile and Boundary Layers on Thermal Efficiency of Solar Liquid Collector Enhanced with Coiled Wire Inserts

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Abstract: Coiled wire inserts are commonly used heat transfer augmentation technique applied in tubular heat exchangers and solar liquid collectors. Coiled wire inserts enhance heat transfer by perturbing the boundary layers formed in the vicinity of the tube wall. The thickness of the wire insert determines the extent of boundary layer disturbed. The heat transfer initially increases with increasing wire thickness but if wire thickness is further increased the heat transfer is reduced due to acceleration of core flow. Dimensionless parameters Pitch of coil to tube diameter ratio and wire thickness to tube diameter ratio have been popular parameters in study of heat transfer enhancement and a number of studies have been conducted to optimize these parameters in order to maximize heat transfer. It is contemplated that wire thickness is one aspect which affect the heat transfer rate but it does not explore much about other factors such as velocity of the outermost fluid layer which is disturbed by wire coil in laminar fully developed flow through a tube and extent to which sub layer or buffer layer in turbulent fully developed flow through tube is disturbed by the coiled wire insert. The present study goes beyond wire thickness to tube diameter ratio and proposes one dimensionless parameter each for laminar and turbulent fully developed flow through tubes. For laminar flow, velocity of fluid at the extreme wire thickness to centerline velocity ratio has been introduced and for turbulent flow, wire thickness to thickness of buffer layer is introduced. The effect of these dimensionless parameters on thermal efficiency of a flat plate type solar liquid collector is studied.

Keywords: Solar flat plate collector; heat transfer augmentation; Coiled wire inserts; W/D Ratio; P/D Ratio; V_W/V_C Ratio; W/T_{buff} Ratio

I. INTRODUCTION

The tube side heat transfer in solar flat plate liquid collectors is increased by enhancing the tube with coiled wire inserts. Coiled wire inserts augment the heat transfer to fluid primarily by disturbing the boundary layer. The thickness of the wire insert determines the extent of boundary layer disturbed. The heat transfer initially increases with increasing wire thickness but if wire thickness is further increased the heat transfer is reduced due to acceleration of core flow. Conventionally dimensionless parameters Pitch of coil to tube diameter ratio (P/D Ratio) and wire thickness to tube diameter ratio (W/D Ratio) have been popular parameters in study of heat transfer enhancement and a number of studies have been conducted to optimize these parameters in order to maximize heat transfer. [1, 2] It is contemplated that wire thickness to tube diameter ratio (W/D Ratio) is one aspect which affect the heat transfer rate but it does not explore much about other factors such as velocity of the outermost fluid layer which is disturbed by wire coil in laminar fully developed flow through a tube and extent to which sub layer or buffer layer in turbulent fully developed flow through tube is disturbed by the coiled wire insert. These factors may help in understanding the conditions when core flow acceleration offsets the heat transfer gain by better mixing of fluid in boundary layer.

II. EXPERIMENTATION AND PROBLEM FORMULATION

A. *Fully Develeoped Laminar Flow Conditions*

In fully developed flow through tubes under laminar flow conditions, the boundary layers encroach entire flow and meet at the centerline. The velocity profile is parabolic and the velocity is maximum at the centerline. Wire thickness disrupts the slow moving layers moving near the tube wall, which results in higher heat transfer. If wire thickness is increased too much the higher heat transfer is offset by the acceleration of the core flow. The important dimensionless number which is of more significance in laminar flow regime than W/D Ratio, is V_W/V_C Ratio. This dimensionless number helps in understanding the fluid behavior in order to optimize the heat transfer from tube with insert wire to the fluid in fully developed laminar flow through tubes. V_W is velocity of fluid layer at a distance (R-W) from the centerline, where W is thickness of insert wire and R is inner radius of the tube.

Experiments were conducted for flow rates of 12 lt/hr, 30 lt/hr, 54 lt/hr and 78 lt/hr with plate and tube type solar collector having absorber plate size of 40cm × 90cm and tube diameter of 10 mm. Copper tube was enhanced with six coiled wire inserts of pitch of 10 mm and 5 mm and wire thickness of 0.8 mm, 1.0 mm and 1.2 mm. Characteristic of Flow in tube for flow rate of 12 lt/hr was laminar flow and Characteristic of flow for flow rates of 30 lt/hr, 54 lt/hr and 78 lt/hr was turbulent.

Thermal efficiency and V_W/V_C Ratio for laminar flow at flow rate of 12 lt/hr for various P/D Ratio and W/D Ratio is tabulated as below.

Table I.

Sl. No	W/D Ratio	Velocity at wire thickness to Centerline velocity Ratio	Thermal Efficiency %	
			P/D Ratio = 1	P/D Ratio = 0.5
1.	0.08	0.29	33.49	40.18
2.	0.10	0.36	36.64	41.92
3.	0.12	0.42	39.75	43.36

Thermal efficiency at various V_w/V_c Ratio in laminar flow

B. *Fully Develeoped Laminar Flow Conditions*

Fully developed flow through tubes or pipes can be divided into three zones along Y-direction, which are Sub laminar zone, Buffer zone and Turbulent zone. Sub laminar zone is extremely thin, in which viscous forces are dominating forces and flow remains laminar. In the buffer zone viscous and turbulent both the forces are equally present and influence the flow characteristics. Beyond the buffer zone, there is turbulent zone where only Reynolds stresses are dominating and flow is fully turbulent.

The important dimensionless number which is of more importance in turbulent flow regime than W/D Ratio, is W/T_{buff} Ratio. This dimensionless number helps in understanding the fluid behavior in order to optimize the heat transfer from tube with insert wire to the fluid in fully developed turbulent flow through tubes. T_{buff} is thickness of buffer layer under flow conditions and

D is inner diameter of the tube. Heat transfer to fluid from tube wall increases as more and more buffer layer is disturbed by the insert wire thickness. But if buffer layer is disturbed beyond a limit by thickness of insert wire, the heat transfer starts decreasing due to acceleration of core flow.

Thermal efficiency, Thickness of Buffer layer and W/T_{buff} Ratio for flow characterized as turbulent flow for P/D Ratio=1 and various W/D Ratio is tabulated as below.

Table II.

Sl. No.	Flow Rate	P/D Ratio	W/D Ratio	Thickness of Buffer Layer(mm)	W/T_{buff} Ratio * 100 (%)	Thermal Efficiency (%)
1.	30 lt/hr	1	0.08	2.328	34.34	34.64
2.	30 lt/hr	1	0.10	2.029	49.28	38.66
3.	30 lt/hr	1	0.12	1.805	66.48	40.50
4.	54 lt/hr	1	0.08	1.413	55.90	36.21
5.	54 lt/hr	1	0.10	1.204	83.05	39.77
6.	54 lt/hr	1	0.12	1.069	112.25	41.76
7.	78 lt/hr	1	0.08	0.998	80.16	37.78
8.	78 lt/hr	1	0.10	0.875	114.28	40.22
9.	78 lt/hr	1	0.12	0.775	154.83	41.16

Thermal efficiency at various W/T_{buff} Ratio for P/D Ratio=1 in turbulent flow

Thermal efficiency, Thickness of Buffer layer and W/T_{buff} Ratio for flow characterized as turbulent flow for P/D Ratio=0.5 and various W/D Ratio is tabulated as below.

Table III.

Sl. No.	Flow Rate	P/D Ratio	W/D Ratio	Thickness of Buffer Layer(mm)	W/T_{buff} Ratio * 100 (%)	Thermal Efficiency (%)
1.	30 lt/hr	0.5	0.08	1.536	52.08	41.34
2.	30 lt/hr	0.5	0.10	1.326	75.41	43.07
3.	30 lt/hr	0.5	0.12	1.162	103.22	44.09
4.	54 lt/hr	0.5	0.08	0.912	87.71	42.24
5.	54 lt/hr	0.5	0.10	0.786	127.22	43.75
6.	54 lt/hr	0.5	0.12	0.688	174.41	44.78
7.	78 lt/hr	0.5	0.08	0.661	121.02	43.08
8.	78 lt/hr	0.5	0.10	0.569	175.74	44.09
9.	78 lt/hr	0.5	0.12	0.499	240.48	44.62

Thermal efficiency at various W/T_{buff} Ratio for P/D Ratio=0.5 in turbulent flow

C. ***Data Reduction***

Velocity profile in laminar flow is given by

$$\frac{V}{Vc} = 1 - \left(\frac{Y}{R}\right)^2$$

Where V_C is centerline velocity, V is velocity of flow at distance Y from centerline and R is radius of tube. The thickness of Buffer layer T_{buff} in turbulent flow is given by

$$\frac{T_{buff}U^*}{\nu} = 70 \text{ , where } U^* = (\frac{\tau_w}{\rho})^{1/2} \text{ and } \tau_w = -(\frac{dp}{dx})\frac{D}{4}$$

Where T_{buff} is thickness of buffer layer in fully developed turbulent flow through a tube, U^* is friction velocity, ν is kinematic viscosity, τ_w is wall shear stress, ρ is density, D is diameter of tube and (dp/dx) is pressure gradient of flow along length of tube.

The thermal efficiency of solar liquid collector

$$\eta_{th} = \frac{m c_p \Delta t}{GA} \quad [3, 4, 5]$$

Where η_{th} is thermal efficiency, m is mass flow rate, c_p is specific heat at constant pressure, Δt is temperature difference, G is global solar irradiance and A is area of absorber plate.

III. Result, Analysis and Discussions

A. *Effect of Velocity profile under Laminar Flow Conditions*

The thermal efficiency Versus V_W/V_C Ratio of flat plate type solar liquid collector enhanced with coiled wire insert is plotted for P/D Ratio=1.0 and 0.5 as below.

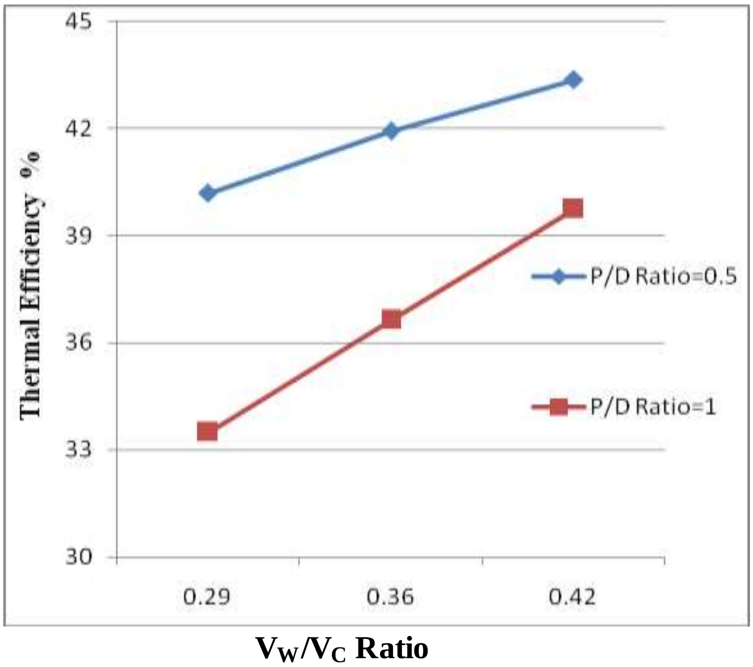

Figure 1: Thermal efficiency Vs. V_W/V_C Ratio in laminar flow

The thermal efficiency is observed to increase till a layer moving with velocity 0.42 times the V_C (V_W/V_C Ratio = 0.42) is disturbed by the coiled wire insert in both the cases of P/D Ratio=1.0 and

0.5 . Within the experimental limitations, it could not be established the V_W/V_C Ratio beyond which the efficiency starts decreasing.

B. Effect of Boundary Layer Thickness under Laminar Flow Conditions

The effect of boundary layer thickness is separately studied for P/D Ratio = 1 and for P/D Ratio = 0.5. The effect of viscous forces is present up to buffer layer in a fully developed turbulent flow in a tube.

The thermal efficiency Versus W/T_{buff} Ratio in fully developed turbulent flow graph for P/D Ratio=1 is plotted as below.

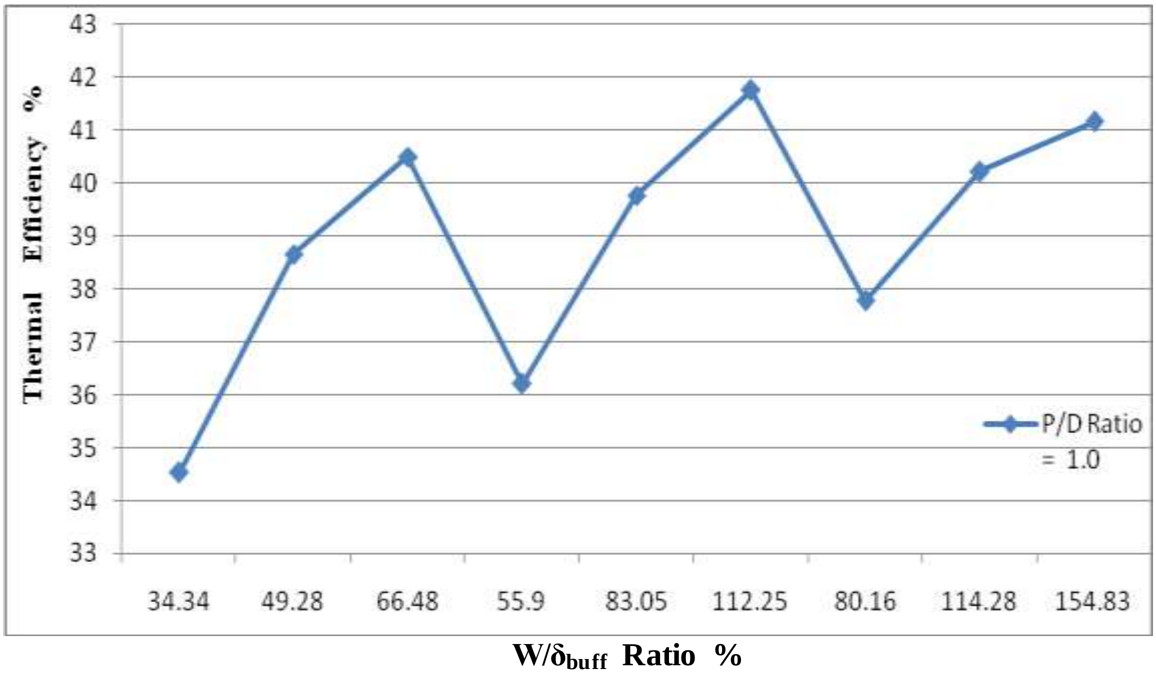

Figure 2: Thermal efficiency Vs. W/T_{buff} Ratio for P/D Ratio = 1 in turbulent flow

The maximum thermal efficiency for P/D Ratio = 1 is obtained at W/T_{buff} Ratio = 112.25 % or for wire thickness of 1.12 times the buffer layer thickness. The thermal efficiency is noticed to decline beyond this ratio.

Similarly, The maximum thermal efficiency for P/D Ratio = 0.5. is obtained at W/T_{buff} Ratio = 174.41 % or for wire thickness of 1.74 times the buffer layer thickness. The thermal efficiency is noticed to decline beyond this ratio.

The thermal efficiency Versus W/T_{buff} Ratio in fully developed turbulent flow graph for P/D Ratio = 0.5 is plotted on page below

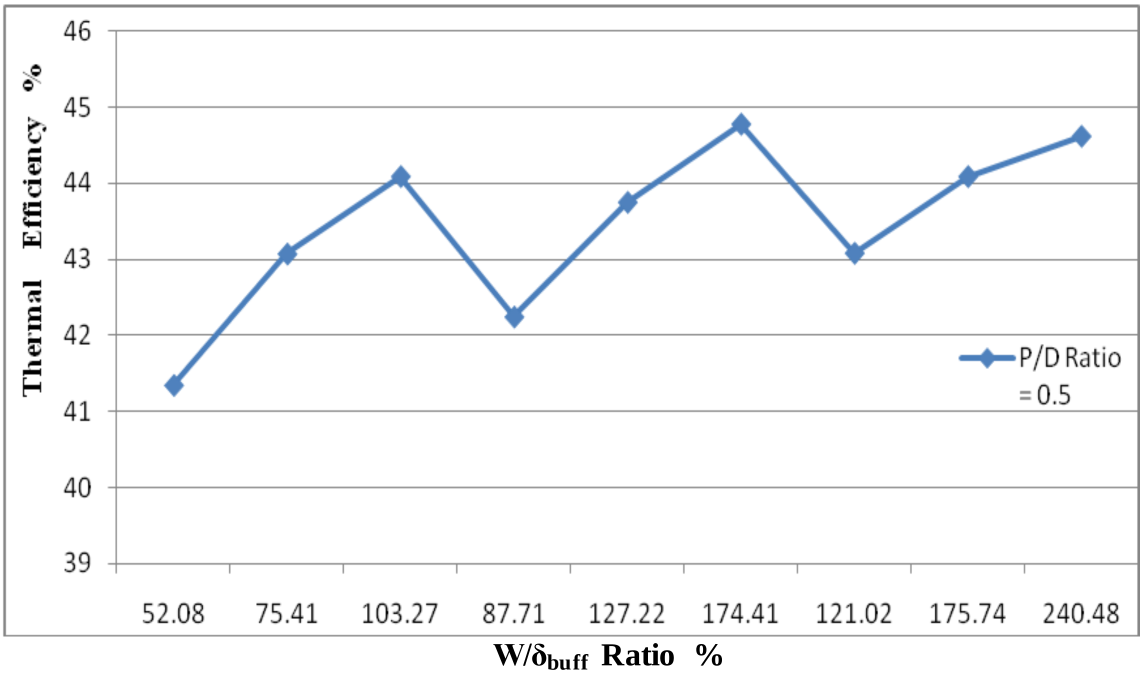

Figure 3: Thermal efficiency Vs. W/T_{buff} Ratio for P/D Ratio = 0.5 in turbulent flow

IV. CONCLUSION

In laminar flow conditions, The thermal efficiency of flat plate type solar liquid collector enhanced with coiled wire insert is observed to increase till a layer moving with velocity 0.42 times the centerline velocity (V_W/V_C Ratio = 0.42) is disturbed by the coiled wire insert. Within the experimental limitations, it could not be established the V_W/V_C Ratio beyond which the efficiency starts decreasing due to acceleration of core flow.

In turbulent flow conditions, The thermal efficiency of flat plate type solar liquid collector enhanced with coiled wire insert is observed to increase till wire thickness of 1.12 times the buffer layer thickness for P/D Ratio = 1 and till wire thickness of 1.74 times the buffer layer thickness for P/D Ratio =0.5. The decrease in thermal efficiency beyond this limit may be precursor to core flow acceleration.

Nomenclature

D	Inner Diameter of Tube	[m]	R	Inner Radius of Tube	[m]
P	Pitch of Coiled wire insert	[m]	V_w	Velocity at distance (R-W)	[m/s]
W	Thickness of coiled wire insert wire	[m]	V_c	Centerline Velocity	[m/s]
T_{buff}	Thickness of Buffer layer	[m]	V	Velocity at distance Y	[m/s]
Y	Radial distance from centerline	[m]	u^*	Friction Velocity	[m/s]
ν	Kinetic viscosity	[m^2/s]	ρ	Density	[kg/m^3]
τ_w	Shear stress at wall	[n/m^2]	*dP/dx*	Pressure change over length x	[n/m^3]
η_{th}	Thermal Efficiency	[-]	m	Mass flow rate	[kg/sec]
c_p	Specific heat	[J/kg K]	*Δt*	Temperature difference	[^{0}c]
G	Global Solar Irradiance	[watt/m^2]	A	Area of absorber plate	[m^2]

V. REFERENCES

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