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Original Research Article

Thermodynamical And Experimental Analysis of Design Parameters of a Heat Pipe Air Recuperator

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Abstract

This study is a follow up of the article named as “Design And Production of High Temperature Heat Pipe Heat Recovery Units”, and it contains the thermodynamical and experimental analysis of the design parameters of “Heat Pipe Air Recuperator” prototype of which project and design fundamentals presented and thereafter the production process has been completed by the previous mentioned study. The heat energy of the high temperature waste flue gases which are the exhaust product of a boiler or of an equipment producing heat energy has been recovered through the use of the designed “Heat Pipe Air Recuperator” which is a “High Temperature Heat Pipe Heat Recovery Unit”. This current study presents the thermodynamical and experimental analysis for the design parameters of Heat Pipe Air Recuperator.

Keywords: Heat pipe, heat pipe air recuperator, energy and fuel saving, waste heat recovery, exhaust gases, thermodynamical and experimental analysis

INTRODUCTION

The heat energy of the high temperature waste flue gases which are the exhaust product of a boiler or of an equipment producing heat energy has been recovered through the use of a “Heat Pipe Air Recuperator” which is a “High Temperature Heat Pipe Heat Recovery Unit”. This current study presents the thermodynamical and experimental analysis for the design parameters of “Heat Pipe Air Recuperator”.

An experimental setup consisting of flow - velocity control, temperature control systems, thermoregulator, heaters and fans has been established and assembled with the heat pipe air recuperator and its connection ducts, in order to realize the operating tests. The measurement and monitoring devices required for measuring the experiment implementation temperatures and flow rates has been provided and calibration processes were conducted.

The experimental setup system coupled with the heat pipe air recuperator and its connection ducts has been started, so the operating data have been provided. These data and the results obtained by the experiments shall be explained in detail at the following sections of this study.

The first part of the experimental setup system is connected to the bottom duct side which is also mounted with the heat pipe air recuperator and the second part of the experimental setup system is connected to the upper duct which is at the opposite side.

The bigger part, that is connected to the bottom duct side, is consisting of higher capacity electric heater group and fan system. The high temperature air produced by this bigger part, shall represent the high temperature waste exhaust gases.

The smaller part of the experimental setup connected to the upper duct, mounted with the heat pipe air recuperator and its duct system at the opposite side, is consisting of lower capacity electric heater group and fan system. The low temperature air produced by this smaller part shall represent the ambient air to be heated by the heat pipe air recuperator.

The high temperature air representing the high temperature waste exhaust gases flowing through the bottom duct shall heat the ambient air flowing through the upper duct, by means of the heat exchange to be realized via heat pipe air recuperator system.

Materials and Methods

The Technical Specifications of the Devices and Equipment used for the Experimental Setup System

The fluids operated for the experimental setup are named as below:

The “Heater Fluid” : High temperature air (Within the bottom duct of the Recuperator).
The “Heated Fluid” : Ambient air. (Within the upper duct of the Recuperator).
The “Working Fluid” : Water (Within the heat pipes of the Recuperator)

The technical specification of the higher capacity electric heater group is as follows: the total capacity is 20 kWe and consisting of 4 stages and each of them is 5 kWe. The high temperature air produced by this higher capacity heater group shall represent the high temperature waste exhaust flue gases.

H_1 Higher Capacity Heater Stages: H_{1-1}, H_{1-2}, H_{1-3}, H_{1-4}

M_1 Electric Motor and Fan is connected to the H_1 Higher Capacity Heater and having a capacity of 0.37 kWe, 2800 rpm, 2100 m^3/h in power, rpm and flow rate, respectively.

S_1 Frequency – Controller is used for the adjustment of flow rate of the high temperature air by changing the rpm of the M_1 motor and fan velocity.

The technical specifications of the lower capacity electric heater group are as follows: the total capacity is 5 kWe and consisting of 1 stage. This lower capacity heater group shall be used for the adjustment of inlet temperature of ambient air to be heated by the recuperator.

H_2 Lower Capacity Heater: H_2

M_2 Electric Motor and Fan is connected to the H_2 Lower Capacity Heater and having a capacity of 0.37 kWe, 2800 rpm, 2100 m^3/h in power, rpm and flow rate, respectively.

S_2 Frequency – Controller is used for the adjustment of flow rate of the ambient air by changing the rpm of the M_2 motor and fan velocity.

Project Systematic, Methods and Design Parameters

Identification of Measurement Points of Temperature and Flow Rate – Velocity for Heat Pipe Air Recuperator

It has been decided to locate the temperature measurement points on the front and back inlet-outlet channels of the recuperator. The temperature measurement points are single points located at the middle of each inlet and outlet sections.

The measurement points of flow rate – velocity is calculated and determined according to the “Chebyshev Method” and these measurement points are available on Fig.1.

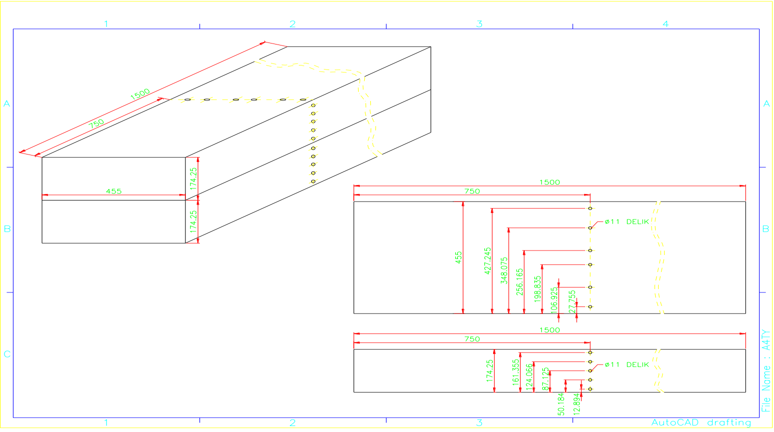

Fig.1. Identification of Measurement Points of Temperature and Flow Rate – Velocity for Heat Pipe Air Recuperator by “Chebyshev Method.

Identification of Measurement Probes and Sensors Used for Experiments

The temperature, flow rate – velocity measurement probes and sensors used for the experiments have been connected to a data logger device and indicated by Table 1.

Table 1. The measurement probes, sensors used for experiments and the related measurement parameters.

Name of Measurement Probe and Sensor	**Function of Measurement Probe and Sensor**	**Measurement Unit**	**Measurement Parameter**
1.1. Probe	Temperature Measurement	˚C	Tg_o
2.1. Probe	Temperature Measurement	˚C	Ta_i
3.1. Probe	Velocity Measurement	m/s	m_g
3.2. Probe	Temperature Measurement	˚C	Tg_i
4.1. Probe	Velocity Measurement	m/s	m_a
4.2. Probe	Temperature Measurement	˚C	Ta_o
C_1 Sensor	Temperature Measurement	˚C	Tg_i
C_2 Sensor	Temperature Measurement	˚C	Ta_o
S_1 Sensor	Velocity Measurement (Frequency Adjustment for Motor rpm)	Hz	$m_{g,}$ $Vg,_i$
S_2 Sensor	Velocity Measurement (Frequency Adjustment for Motor rpm)	Hz	$m_{a,}$ $Va,_o$

Recuperator outlet temperature of exhaust gas, Tg_o
Recuperator inlet temperature of ambient air, Ta_i
Mass flow rate of exhaust gas, m_g
Recuperator inlet temperature of exhaust gas, Tg_i
Mass flow rate of ambient air, m_a
Recuperator outlet temperature of ambient air, Ta_o
Recuperator inlet velocity of exhaust gas, $Vg,_i$
Recuperator outlet velocity of embient air, $Va,_o$

Experimental Setup System

The experimental setup system established to realize the thermodynamical and experimental analysis for the design parameters of Heat Pipe Air Recuperator is shown in Fig. 2, the flow directions for exhaust gas and ambient air through the experimental setup system of Heat Pipe Air Recuperator is shown in Fig.3. The control panel and the connection detail for measurement probes, sensors, heaters, motors and fans are indicated on Fig.4. The perspective view for complete experimental setup system and Heat Pipe Air Recuperator is shown in Fig.5.

Fig 2. The Experimental Setup System of Heat Pipe Air Recuperator

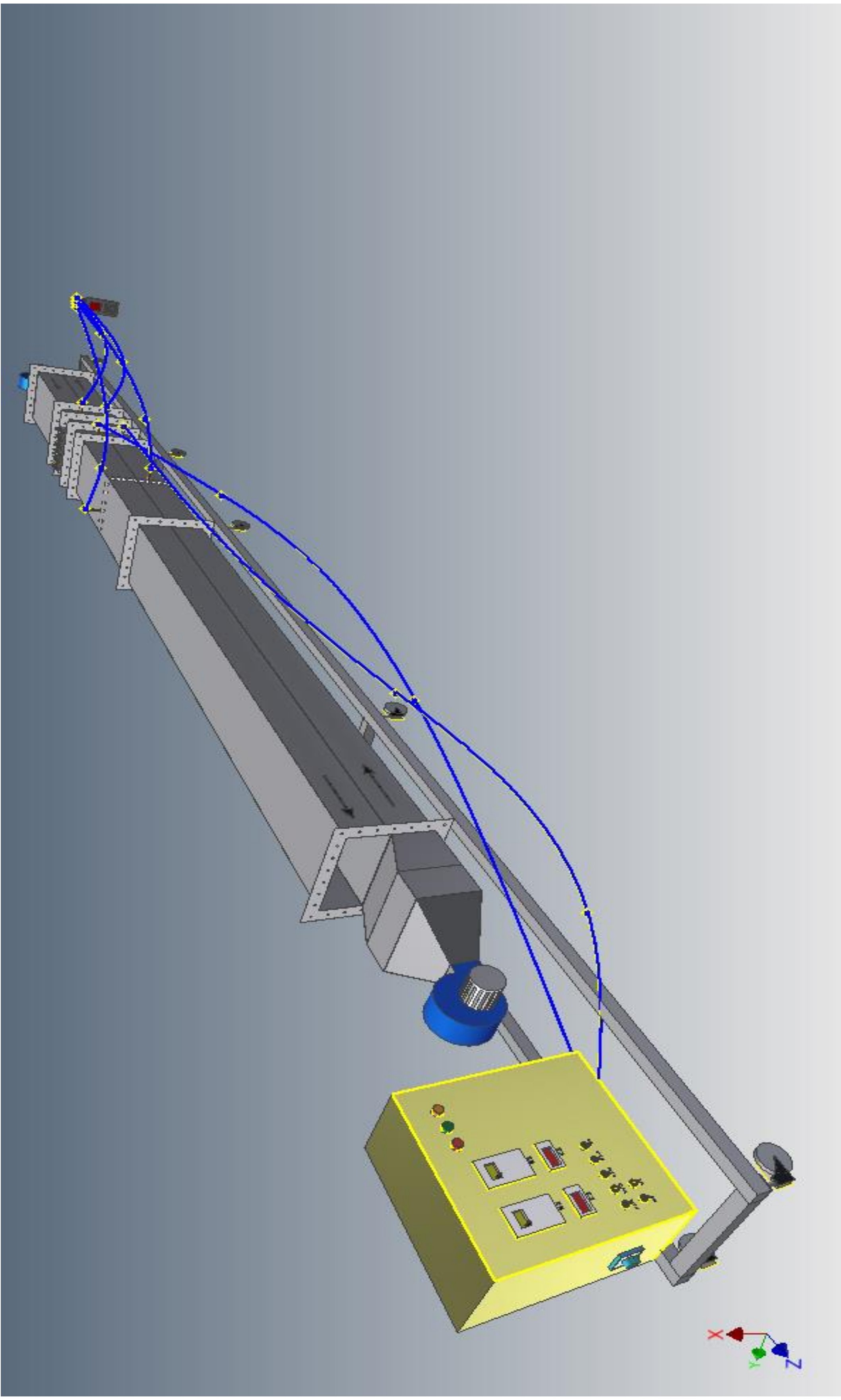

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Fig.3. The Flow Directions for Exhaust Gas and Ambient Air through the Experimental Setup System of Heat Pipe Air Recuperator

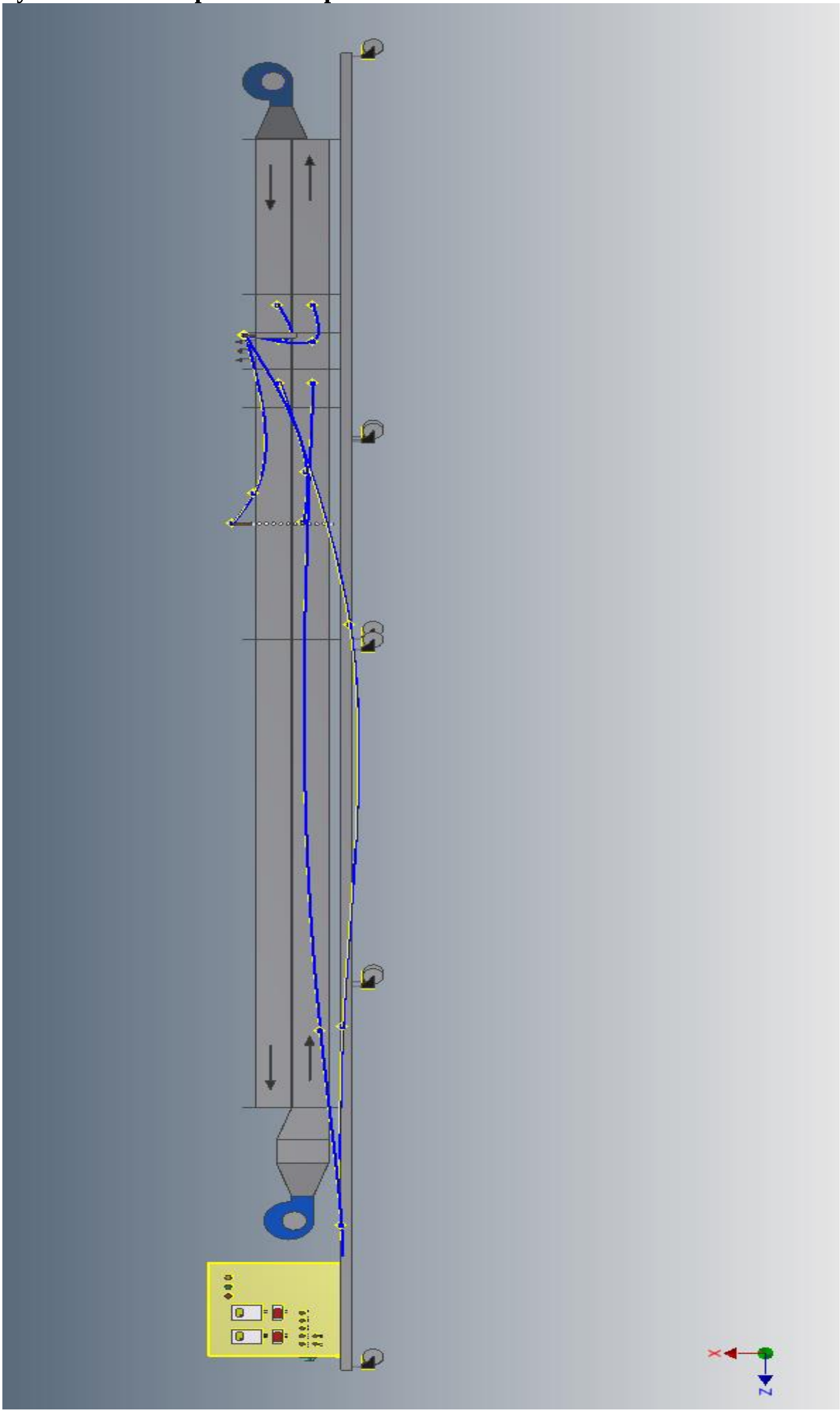


Fig. 4. The Control Panel and the Connection Detail for Measurement Probes, Sensors, Heaters, Motors and Fans

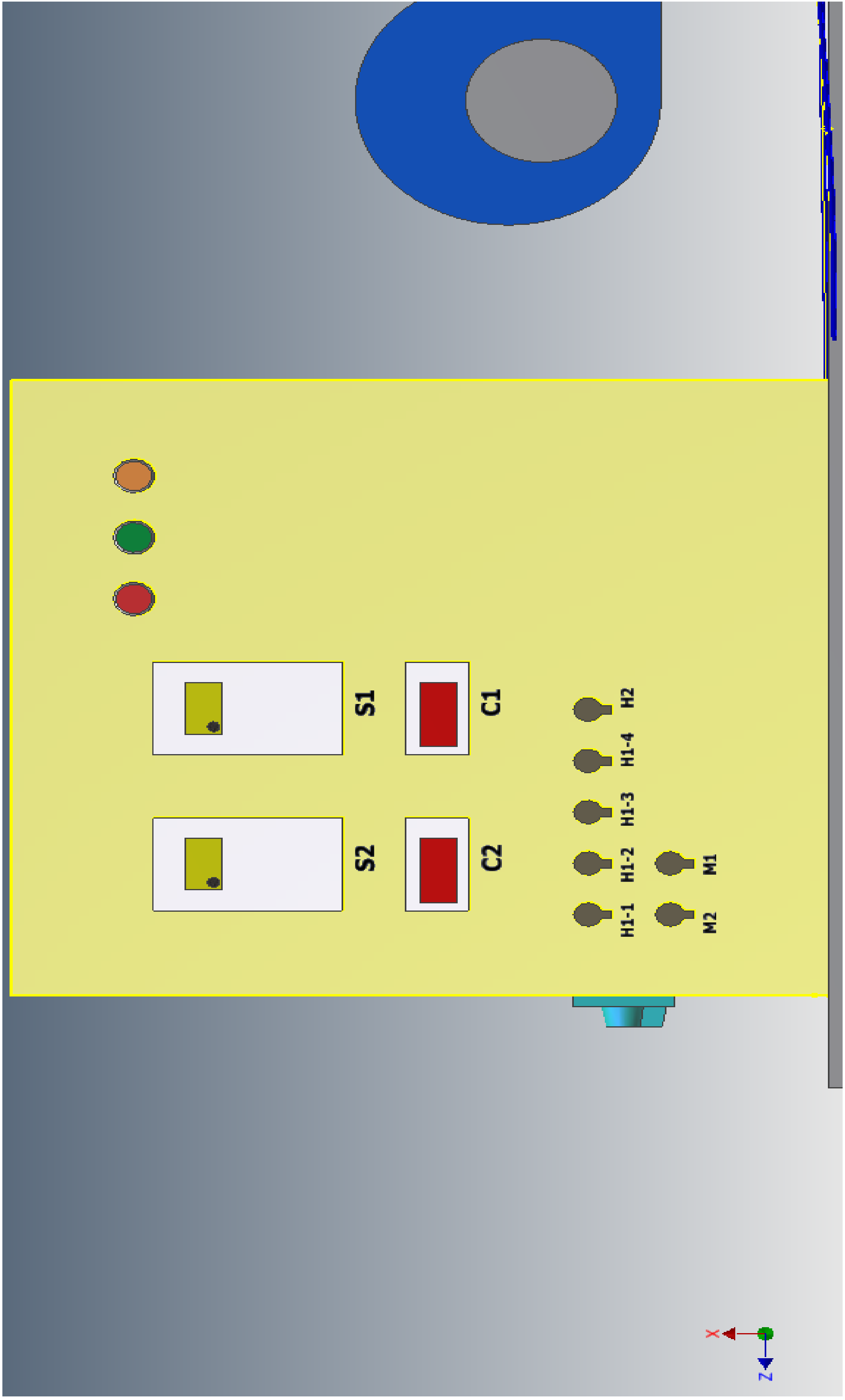
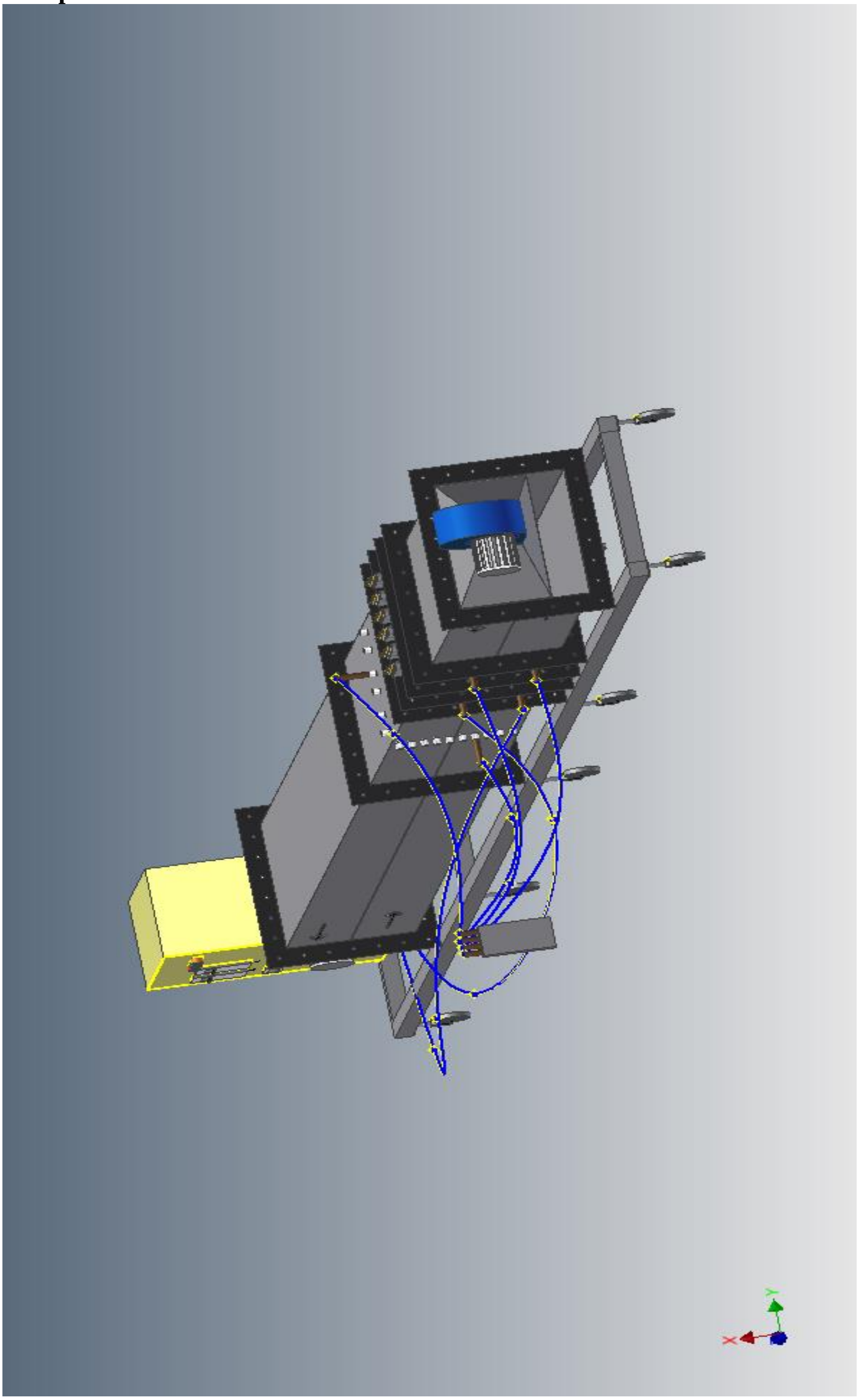


Fig.5. The Perspective View for Complete Experimental Setup System and Heat Pipe Air Recuperator



Measurement Uncertainty Analysis and its Impact on the Results

The calibrations of measurement probes and sensors used for the experiments have been carried out in order to ensure the accuracy of experimental results.

The measurement uncertainty analysis has been realized for the probes during the calibration process and a calibration equation has been obtained accordingly in order to state the measurement uncertainty and so, the calibration equation is written as follows:

$$y = 0.014 + x - 1.13*10^{-4} x^{2} + 8.88*10^{-7}x^{3} \qquad (1)$$

The data provided by the experiments have been corrected by applying measurement uncertainty analysis as described above and Eq.1. Therefore, it is definitely possible to say that the measurement results obtained by the experiments are completely reliable and similarly it is also possible to say that the recuperator effectiveness rates are absolutely correct.

Results and Discussion

Effectiveness of Heat Pipe Air Recuperator

The various operating cases of heat pipe air recuperator can be obtained by applying various operating parameters such as temperature, flow rate, capacity and effectiveness. The values for the effectiveness rate can be determined by Eq. 5

The other related equations are as follows:

$$Q_{Total} = m_g \text{ x } (hg_i - hg_o) = m_g \text{ x } cp_g \text{ x } (Tg_i - Tg_o) \qquad (2)$$

$$Q_{Total} = m_a \text{ x } (ha_o - ha_i) = m_a \text{ x } cp_a \text{ x } (Ta_o - Ta_i) \qquad (3)$$

The maximum capacity rate of heated ambient air obtained by the recuperator can be stated by Eq. 4

$$Q_{Total} = m_a \text{ x } cp_a \text{ x } (Tg_i - Ta_i) \qquad (4)$$

Eq.3 is divided by Eq.4 and the following equation will be obtained;

$$E = \frac{ma \text{ x } cpa \text{ x } (Tao - Tai)}{ma \text{ x } cpa \text{ x } (Tgi - Tai)} \text{ x } 100 \ \%$$

assuming that the specific heats are constant;

$$E = \frac{(Tao - Tai)}{(Tgi - Tai)} \text{ x } 100 \ \% \qquad (5)$$

E, is the % effectiveness rate of heat pipe air recuperator.

The effectiveness rate , E, described with Eq. 5 can be calculated by using the recuperator design values mentioned as follows:

$Tg_i = 260$ ˚C
$Tg_o = 177$ ˚C
$Ta_i = 27$ ˚C
$Ta_o = 122$ ˚C

The above temperature values are substituted in Eq. 5 and the effectiveness is calculated as below.

$$E = \frac{122 - 27}{260 - 27} \text{ x } 100$$

E = 40.7725 %

The above calculated effectiveness value can be approximately accepted as 41% and, therefore the effectiveness value of heat pipe air recuperator is E = 41% at design conditions.

The other effectiveness rates are obtained by the experimental tests depending upon the recuperator operating parameters and stated by the following tables.

The Data Tables Obtained by Experiments

The data obtained by the experiments have been stated by the below tables.

These tables have been organized by commissioning the H_{1-1}, H_{1-2}, H_{1-3}, H_{1-4} and H_2 heater groups providing various particular operating temperature conditions for heat pipe air recuperator.

The flow rates for exhaust gas and ambient air are adjusted by the M_1, M_2 motor frequency rates and rpm values and these flow rates are then combined together with the changing temperature values. As the heater groups start and stop step by step, the motor frequency and rpm values are adjusted gradually decreasing and increasing. Therefore, a lot of combination of temperature and flow rates can be obtained by this method.

The obtained data and parameters of 31 experimental operations are summarized by the below tables (Table 2 – Table 32). These tables present the corrected measured data according to the procedure of measurement uncertainty analysis and these values indicated on the below tables are the “verified accurate results”. Table 33 and Table 34 present the design parameters and results either exhaust gas or air used for the tests, respectively.

Table 2. Parameters and Experimental Data Results– 1

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.064
m_a	kg/s	0.065
Tg_i	˚C	24.96
Tg_o	˚C	24.26
Ta_i	˚C	24.18
Ta_o	˚C	24.56
hg_i	kJ/kg	298.52
hg_o	kJ/kg	297.85
ha_i	kJ/kg	297.77
ha_o	kJ/kg	298.13
Q_{Total} (Recuperator)	kW	0.0331
Effectiveness (Recuperator)	%	48.72

Table 3. Parameters and Experimental Data Results – 2

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.062
m_a	kg/s	0.062
Tg_i	˚C	60.70
Tg_o	˚C	54.22
Ta_i	˚C	26.80
Ta_o	˚C	28.45
hg_i	kJ/kg	334.52
hg_o	kJ/kg	327.97
ha_i	kJ/kg	300.28
ha_o	kJ/kg	301.93
Q_{Total} (Recuperator)	kW	0.2542
Effectiveness (Recuperator)	%	4.87

Table 4. Parameters and Experimental Data Results – 3

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.084
m_a	kg/s	0.084
Tg_i	˚C	23.07
Tg_o	˚C	22.47
Ta_i	˚C	21.80
Ta_o	˚C	22.37
hg_i	kJ/kg	296.70
hg_o	kJ/kg	296.13
ha_i	kJ/kg	295.48
ha_o	kJ/kg	296.03
Q_{Total} (Recuperator)	kW	0.0470
Effectiveness (Recuperator)	%	44.88

Table 5. Parameters and Experimental Data Results – 4

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.079
m_a	kg/s	0.140
Tg_i	˚C	76.75
Tg_o	˚C	67.77
Ta_i	˚C	25.32
Ta_o	˚C	26.95
hg_i	kJ/kg	350.76
hg_o	kJ/kg	341.67
ha_i	kJ/kg	298.86
ha_o	kJ/kg	300.42
Q_{Total} (Recuperator)	kW	0.4682
Effectiveness (Recuperator)	%	3.17

Table 6. Parameters and Experimental Data Results – 5

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.068
m_a	kg/s	0.140
Tg_i	˚C	79.25
Tg_o	˚C	70.36
Ta_i	˚C	25.61
Ta_o	˚C	27.95
hg_i	kJ/kg	353.29
hg_o	kJ/kg	344.29
ha_i	kJ/kg	299.14
ha_o	kJ/kg	301.43
Q_{Total} (Recuperator)	kW	0.4663
Effectiveness (Recuperator)	%	4.37

Table 7. Parameters and Experimental Data Results – 6

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.072
m_a	kg/s	0.139
Tg_i	˚C	81.75
Tg_o	˚C	73.65
Ta_i	˚C	25.95
Ta_o	˚C	27.95
hg_i	kJ/kg	355.82
hg_o	kJ/kg	347.62
ha_i	kJ/kg	299.46
ha_o	kJ/kg	301.43
Q_{Total} (Recuperator)	kW	0.4321
Effectiveness (Recuperator)	%	3.59

Table 8. Parameters and Experimental Data Results – 7

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.073
m_a	kg/s	0.137
Tg_i	˚C	82.75
Tg_o	˚C	75.00
Ta_i	˚C	26.32
Ta_o	˚C	28.95
hg_i	kJ/kg	356.84
hg_o	kJ/kg	348.99
ha_i	kJ/kg	299.82
ha_o	kJ/kg	302.44
Q_{Total} (Recuperator)	kW	0.4659
Effectiveness (Recuperator)	%	4.67

Table 9. Parameters and Experimental Data Results – 8

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.046
m_a	kg/s	0.053
Tg_i	˚C	87.65
Tg_o	˚C	71.95
Ta_i	˚C	32.07
Ta_o	˚C	41.89
hg_i	kJ/kg	361.80
hg_o	kJ/kg	345.90
ha_i	kJ/kg	305.59
ha_o	kJ/kg	315.51
Q_{Total} (Recuperator)	kW	0.6285
Effectiveness (Recuperator)	%	17.67

Table10. Parameters and Experimental Data Results – 9

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.046
m_a	kg/s	0.053
Tg_i	˚C	87.35
Tg_o	˚C	72.05
Ta_i	˚C	29.30
Ta_o	˚C	38.90
hg_i	kJ/kg	361.50
hg_o	kJ/kg	346.00
ha_i	kJ/kg	302.79
ha_o	kJ/kg	312.49
Q_{Total} (Recuperator)	kW	0.6135
Effectiveness (Recuperator)	%	16.54

Table 11. Parameters and Experimental Data Results – 10

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.046
m_a	kg/s	0.054
Tg_i	˚C	87.15
Tg_o	˚C	72.15
Ta_i	˚C	27.97
Ta_o	˚C	37.90
hg_i	kJ/kg	361.29
hg_o	kJ/kg	346.11
ha_i	kJ/kg	301.45
ha_o	kJ/kg	311.48
Q_{Total} (Recuperator)	kW	0.6199
Effectiveness (Recuperator)	%	16.78

Table 12. Parameters and Experimental Data Results – 11

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.046
m_a	kg/s	0.054
Tg_i	˚C	87.15
Tg_o	˚C	72.95
Ta_i	˚C	27.11
Ta_o	˚C	36.91
hg_i	kJ/kg	361.29
hg_o	kJ/kg	346.92
ha_i	kJ/kg	300.58
ha_o	kJ/kg	310.48
Q_{Total} (Recuperator)	kW	0.5978
Effectiveness (Recuperator)	%	16.32

Table 13. Parameters and Experimental Data Results – 12

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.046
m_a	kg/s	0.054
Tg_i	˚C	87.65
Tg_o	˚C	73.45
Ta_i	˚C	26.31
Ta_o	˚C	34.92
hg_i	kJ/kg	361.80
hg_o	kJ/kg	347.42
ha_i	kJ/kg	299.81
ha_o	kJ/kg	308.47
Q_{Total} (Recuperator)	kW	0.5645
Effectiveness (Recuperator)	%	14.03

Table 14. Parameters and Experimental Data Results – 13

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.046
m_a	kg/s	0.054
Tg_i	˚C	88.35
Tg_o	˚C	74.95
Ta_i	˚C	25.65
Ta_o	˚C	33.92
hg_i	kJ/kg	362.51
hg_o	kJ/kg	348.94
ha_i	kJ/kg	299.18
ha_o	kJ/kg	307.46
Q_{Total} (Recuperator)	kW	0.5356
Effectiveness (Recuperator)	%	13.18

Table 15. Parameters and Experimental Data Results – 14

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.046
m_a	kg/s	0.054
Tg_i	˚C	88.75
Tg_o	˚C	75.15
Ta_i	˚C	25.42
Ta_o	˚C	33.33
hg_i	kJ/kg	362.92
hg_o	kJ/kg	349.14
ha_i	kJ/kg	298.96
ha_o	kJ/kg	306.86
Q_{Total} (Recuperator)	kW	0.5302
Effectiveness (Recuperator)	%	12.49

Table 16. Parameters and Experimental Data Results – 15

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.045
m_a	kg/s	0.054
Tg_i	˚C	94.46
Tg_o	˚C	81.24
Ta_i	˚C	24.93
Ta_o	˚C	32.33
hg_i	kJ/kg	368.70
hg_o	kJ/kg	355.31
ha_i	kJ/kg	298.49
ha_o	kJ/kg	305.85
Q_{Total} (Recuperator)	kW	0.4999
Effectiveness (Recuperator)	%	10.65

Table 17. Parameters and Experimental Data Results – 16

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.046
m_a	kg/s	0.055
Tg_i	˚C	90.95
Tg_o	˚C	77.84
Ta_i	˚C	23.96
Ta_o	˚C	31.63
hg_i	kJ/kg	365.15
hg_o	kJ/kg	351.87
ha_i	kJ/kg	297.56
ha_o	kJ/kg	305.14
Q_{Total} (Recuperator)	kW	0.5138
Effectiveness (Recuperator)	%	11.45

Table 18. Parameters and Experimental Data Results – 17

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.046
m_a	kg/s	0.055
Tg_i	˚C	91.15
Tg_o	˚C	78.34
Ta_i	˚C	24.73
Ta_o	˚C	31.24
hg_i	kJ/kg	365.35
hg_o	kJ/kg	352.37
ha_i	kJ/kg	298.30
ha_o	kJ/kg	304.75
Q_{Total} (Recuperator)	kW	0.4759
Effectiveness (Recuperator)	%	9.81

Table 19. Parameters and Experimental Data Results – 18

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.046
m_a	kg/s	0.055
Tg_i	˚C	93.16
Tg_o	˚C	80.74
Ta_i	˚C	24.56
Ta_o	˚C	30.84
hg_i	kJ/kg	367.39
hg_o	kJ/kg	354.80
ha_i	kJ/kg	298.13
ha_o	kJ/kg	304.35
Q_{Total} (Recuperator)	kW	0.4606
Effectiveness (Recuperator)	%	9.15

Table 20. Parameters and Experimental Data Results – 19

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.046
m_a	kg/s	0.055
Tg_i	˚C	92.25
Tg_o	˚C	79.64
Ta_i	˚C	24.61
Ta_o	˚C	30.54
hg_i	kJ/kg	366.46
hg_o	kJ/kg	353.69
ha_i	kJ/kg	298.18
ha_o	kJ/kg	304.04
Q_{Total} (Recuperator)	kW	0.4548
Effectiveness (Recuperator)	%	8.77

Table 21. Parameters and Experimental Data Results – 20

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.045
m_a	kg/s	0.055
Tg_i	˚C	93.36
Tg_o	˚C	82.34
Ta_i	˚C	24.81
Ta_o	˚C	30.34
hg_i	kJ/kg	367.59
hg_o	kJ/kg	356.42
ha_i	kJ/kg	298.37
ha_o	kJ/kg	303.84
Q_{Total} (Recuperator)	kW	0.4017
Effectiveness (Recuperator)	%	8.07

Table 22. Parameters and Experimental Data Results – 21

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.044
m_a	kg/s	0.055
Tg_i	˚C	104.50
Tg_o	˚C	86.24
Ta_i	˚C	24.67
Ta_o	˚C	30.24
hg_i	kJ/kg	378.89
hg_o	kJ/kg	360.37
ha_i	kJ/kg	298.24
ha_o	kJ/kg	303.74
Q_{Total} (Recuperator)	kW	0.5586
Effectiveness (Recuperator)	%	6.97

Table 23. Parameters and Experimental Data Results – 22

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.045
m_a	kg/s	0.055
Tg_i	˚C	96.06
Tg_o	˚C	83.34
Ta_i	˚C	24.52
Ta_o	˚C	30.04
hg_i	kJ/kg	370.33
hg_o	kJ/kg	357.44
ha_i	kJ/kg	298.10
ha_o	kJ/kg	303.54
Q_{Total} (Recuperator)	kW	0.4396
Effectiveness (Recuperator)	%	7.72

Table 24. Parameters and Experimental Data Results – 23

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.046
m_a	kg/s	0.055
Tg_i	˚C	94.76
Tg_o	˚C	82.04
Ta_i	˚C	24.49
Ta_o	˚C	30.04
hg_i	kJ/kg	369.01
hg_o	kJ/kg	356.12
ha_i	kJ/kg	298.07
ha_o	kJ/kg	303.54
Q_{Total} (Recuperator)	kW	0.4468
Effectiveness (Recuperator)	%	7.90

Table 25. Parameters and Experimental Data Results – 24

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.077
m_a	kg/s	0.084
Tg_i	˚C	67.28
Tg_o	˚C	58.20
Ta_i	˚C	30.77
Ta_o	˚C	37.11
hg_i	kJ/kg	341.18
hg_o	kJ/kg	332.00
ha_i	kJ/kg	304.28
ha_o	kJ/kg	310.68
Q_{Total} (Recuperator)	kW	0.6222
Effectiveness (Recuperator)	%	17.37

Table 26. Parameters and Experimental Data Results – 25

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.077
m_a	kg/s	0.085
Tg_i	˚C	67.78
Tg_o	˚C	58.90
Ta_i	˚C	28.60
Ta_o	˚C	35.02
hg_i	kJ/kg	341.68
hg_o	kJ/kg	332.70
ha_i	kJ/kg	302.08
ha_o	kJ/kg	308.57
Q_{Total} (Recuperator)	kW	0.6215
Effectiveness (Recuperator)	%	16.39

Table 27. Parameters and Experimental Data Results – 26

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.076
m_a	kg/s	0.085
Tg_i	˚C	69.17
Tg_o	˚C	60.09
Ta_i	˚C	26.91
Ta_o	˚C	33.43
hg_i	kJ/kg	343.09
hg_o	kJ/kg	333.91
ha_i	kJ/kg	300.38
ha_o	kJ/kg	306.96
Q_{Total} (Recuperator)	kW	0.6284
Effectiveness (Recuperator)	%	15.43

Table 28. Parameters and Experimental Data Results – 27

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.076
m_a	kg/s	0.085
Tg_i	˚C	69.47
Tg_o	˚C	60.89
Ta_i	˚C	26.46
Ta_o	˚C	32.43
hg_i	kJ/kg	343.39
hg_o	kJ/kg	334.72
ha_i	kJ/kg	299.95
ha_o	kJ/kg	305.95
Q_{Total} (Recuperator)	kW	0.5844
Effectiveness (Recuperator)	%	13.88

Table 29. Parameters and Experimental Data Results – 28

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.076
m_a	kg/s	0.085
Tg_i	˚C	69.87
Tg_o	˚C	61.49
Ta_i	˚C	26.05
Ta_o	˚C	31.63
hg_i	kJ/kg	343.80
hg_o	kJ/kg	335.32
ha_i	kJ/kg	299.56
ha_o	kJ/kg	305.14
Q_{Total} (Recuperator)	kW	0.5593
Effectiveness (Recuperator)	%	12.74

Table 30. Parameters and Experimental Data Results – 29

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.076
m_a	kg/s	0.086
Tg_i	˚C	70.67
Tg_o	˚C	62.49
Ta_i	˚C	25.10
Ta_o	˚C	30.44
hg_i	kJ/kg	344.61
hg_o	kJ/kg	336.33
ha_i	kJ/kg	298.65
ha_o	kJ/kg	303.94
Q_{Total} (Recuperator)	kW	0.5421
Effectiveness (Recuperator)	%	11.72

Table 31. Parameters and Experimental Data Results – 30

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.076
m_a	kg/s	0.086
Tg_i	˚C	71.27
Tg_o	˚C	63.58
Ta_i	˚C	25.20
Ta_o	˚C	29.74
hg_i	kJ/kg	345.22
hg_o	kJ/kg	337.44
ha_i	kJ/kg	298.75
ha_o	kJ/kg	303.23
Q_{Total} (Recuperator)	kW	0.4882
Effectiveness (Recuperator)	%	9.85

Table 32. Parameters and Experimental Data Results – 31

Measurement Parameter	Measurement Unit	Verified Accurate Results
m_g	kg/s	0.076
m_a	kg/s	0.086
Tg_i	˚C	70.77
Tg_o	˚C	63.68
Ta_i	˚C	25.28
Ta_o	˚C	29.44
hg_i	kJ/kg	344.71
hg_o	kJ/kg	337.54
ha_i	kJ/kg	298.82
ha_o	kJ/kg	302.93
Q_{Total} (Recuperator)	kW	0.4491
Effectiveness (Recuperator)	%	9.14

Table 33. Design Parameters and Results if Exhaust Gas is used for the Tests

Measurement Parameter	Measurement Unit	Verified Accurate Results for Design Parameters
m_g	kg/s	0.274
m_a	kg/s	0.274
Tg_i	˚C	267.99
Tg_o	˚C	178.40
Ta_i	˚C	26.95
Ta_o	˚C	122
hg_i	kJ/kg	619.53
hg_o	kJ/kg	513.98
ha_i	kJ/kg	300.42
ha_o	kJ/kg	396.67
Q_{Total} (Gas Side)	kW	28.9207
Q_{Total} (Air Side)	kW	26.3725
Q_{Total} (Recuperator)	kW	27.6466
Effectiveness (Recuperator)	%	39.44

Table 34. Design Parameters and Results if Air s is used for the Tests

Measurement Parameter	Measurement Unit	Verified Accurate Results for Design Parameters
m_g	kg/s	0.274
m_a	kg/s	0.274
Tg_i	˚C	267.99
Tg_o	˚C	178.40
Ta_i	˚C	26.95
Ta_o	˚C	122
hg_i	kJ/kg	546.77
hg_o	kJ/kg	454.24
ha_i	kJ/kg	300.42
ha_o	kJ/kg	396.67
Q_{Total} (Gas Side)	kW	25.3532
Q_{Total} (Air Side)	kW	26.3725
Q_{Total} (Recuperator)	kW	25.8628

Effectiveness (Recuperator)	%	39.44

The relationships, variations between the values of capacity, effectiveness, temperature and flow rate can be stated by the graphics as shown in Fig.. through the use of the experimental data, parameters and results provided by the tables.

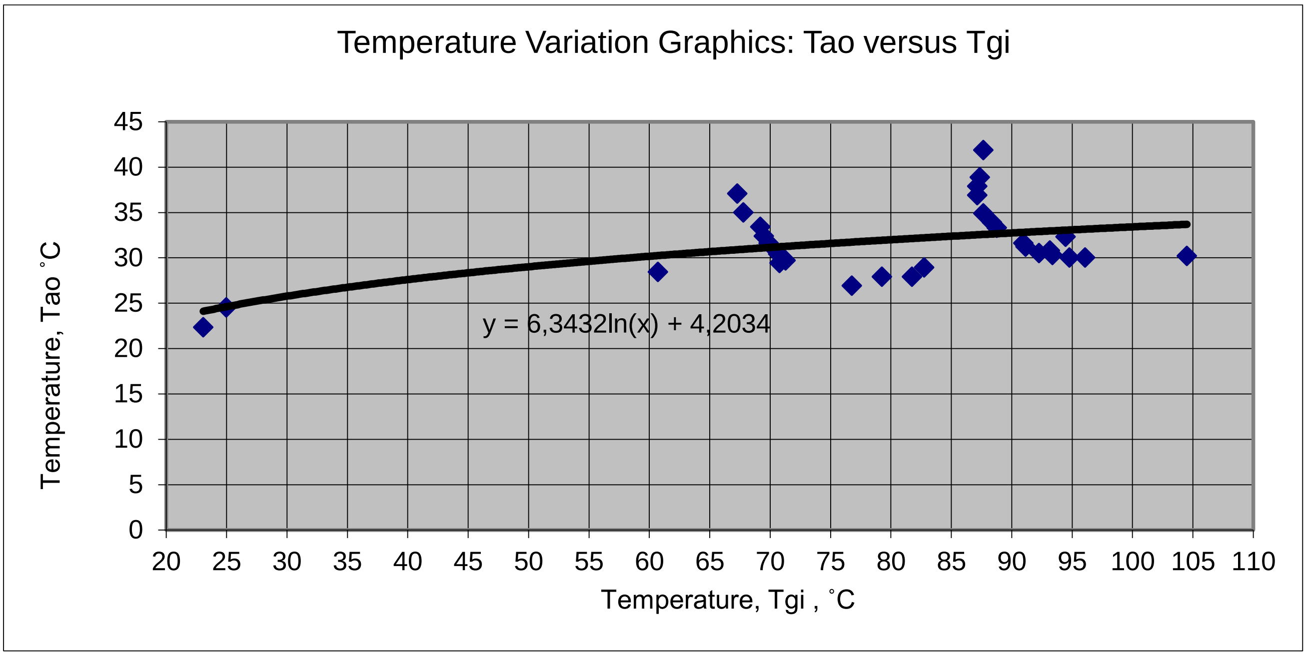


Fig.6. Variations of ambient air outlet temperature, Ta_o versus exhaust gas inlet temperature, Tg_i in accordance with the test results ($m_g \approx m_a$).

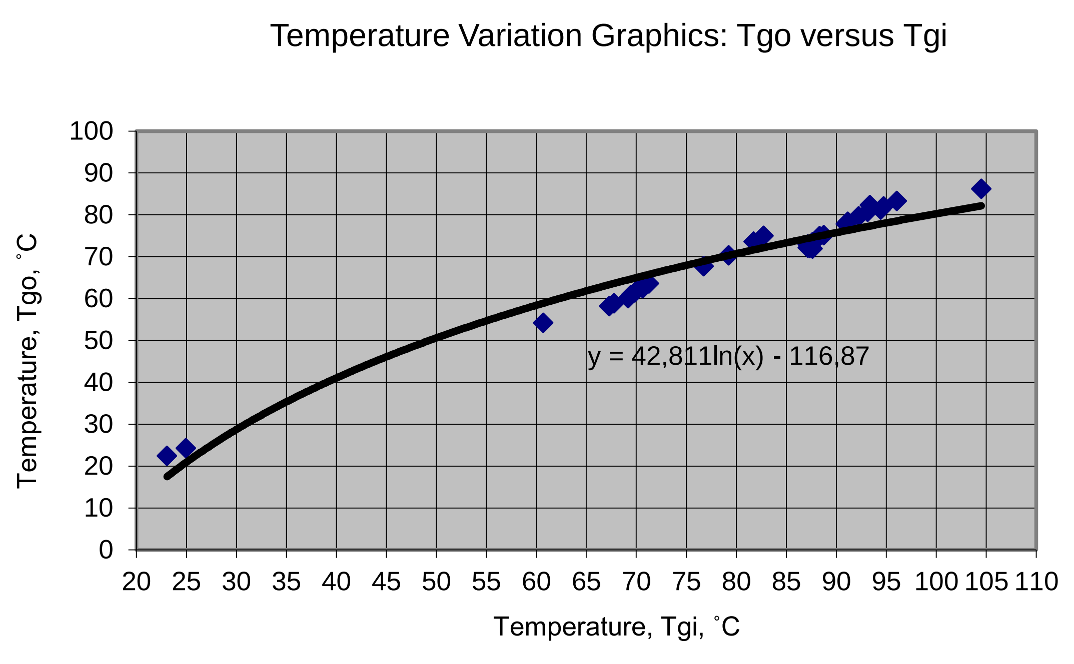


Fig.7. Variations of exhaust gas outlet temperature, Tg_o versus exhaust gas inlet temperature,Tg_i in accordance with the test results ($m_g \approx m_a$).

As a heat pipe air recuperator design rule, the flow rates for exhaust gas and ambient air are always adjusted approximately equal to each other, that is ($m_g \approx m_a$) during the implementation of experimental tests. Fig.6. shows that ambient air outlet temperatures increase when the exhaust gas inlet temperatures increase.

Fig. 7. shows that exhaust gas outlet temperatures also increase when the exhaust gas inlet temperatures increase.

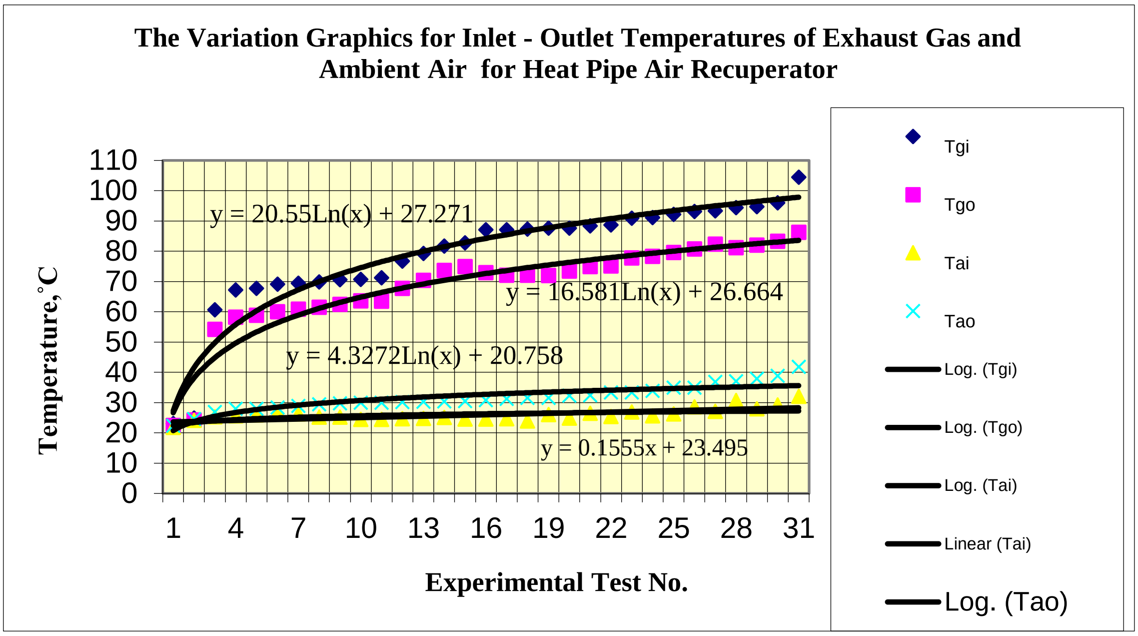


Fig.8. Variations of inlet- outlet temperatures of exhaust gas and ambient air for heat pipe air recuperator, Tgi, Tgo, Tai, Tao (mg≈ma).

Fig.8. shows the variations between the exhaust gas inlet-outlet temperatures, and the ambient air inlet-outlet temperatures. The waste exhaust gas enters the heat pipe air recuperator at a specific temperature and loses out its energy and leaves the recuperator at a lower temperature. On the other hand, the ambient air sent to the recuperator recovers this lost energy and leaves the recuperator at a higher temperature than the inlet temperature rate. Therefore, an energy transfer is realized between the waste exhaust gases and ambient air by means of heat pipe air recuperator system. Apart from that, the variation graphics mentioned on Fig. 8. also shows that the variations are realized as expected and the heat pipe air recuperator is working properly.

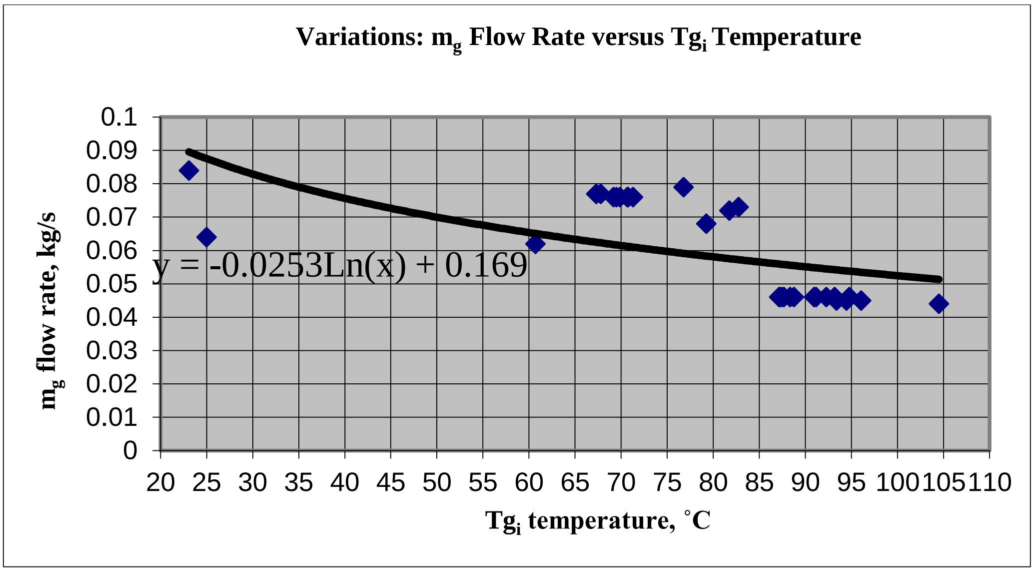


Fig.9. Variations of exhaust gas flow rate, m_g, versus exhaust gas inlet temperature,Tg_i in accordance with the test results ($m_g \approx m_a$).

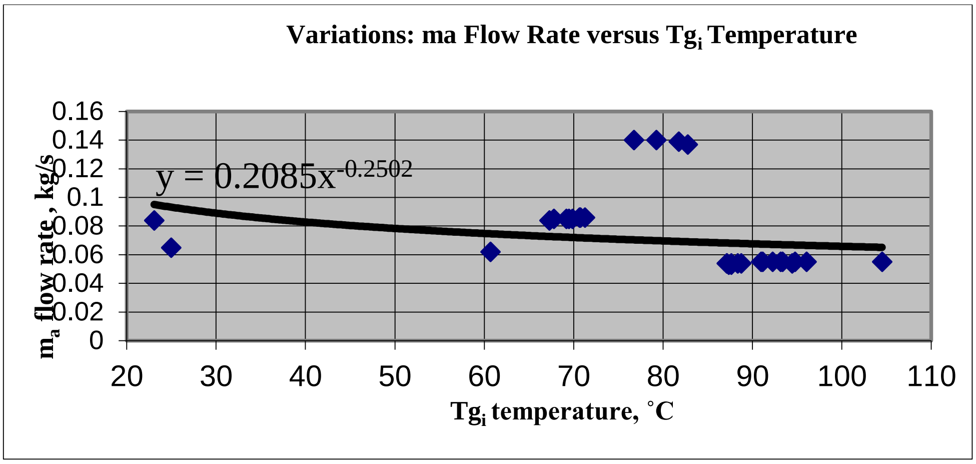


Fig.10. Variations of ambient air flow rate, m_a, versus exhaust gas inlet temperature,Tg_i in accordance with the test results ($m_g \approx m_a$).

Fig.9 states that the exhaust gas flow rates decrease by the exhaust gas inlet temperatures increase on condition that the recuperator capacity remains constant. Fig.10 states the variations of ambient air flow rate by the exhaust gas inlet temperature increase.

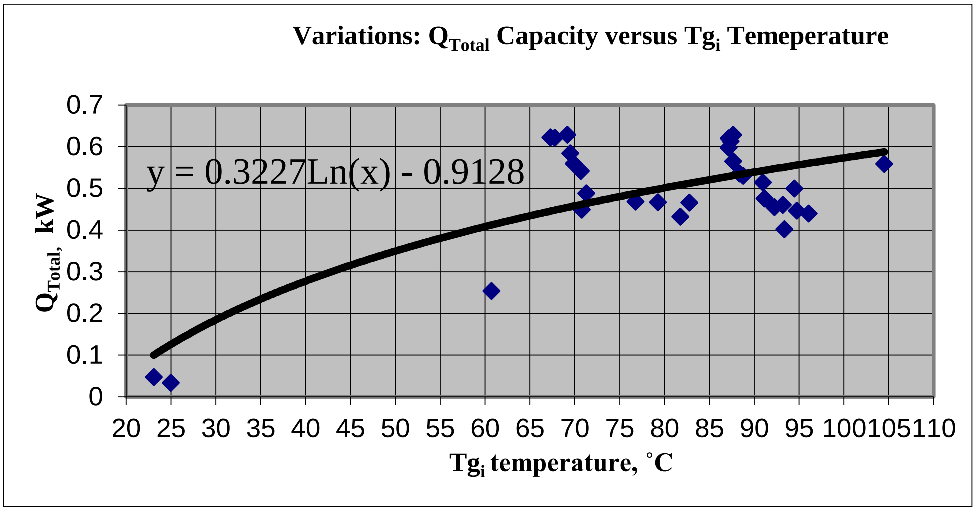


Fig.11. Variations of recuperator capacity, Q_{Total} versus exhaust gas inlet temperature,Tg_i in accordance with the test results ($m_g \approx m_a$).

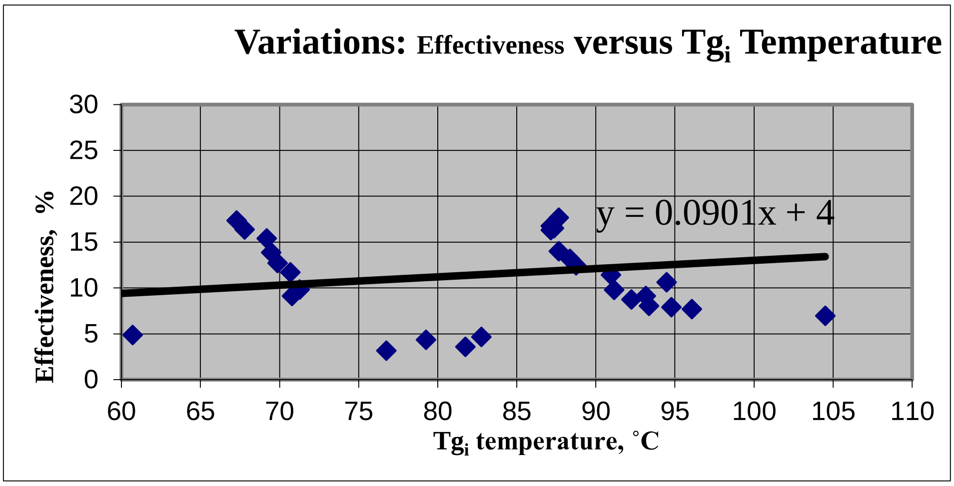


Fig.12. Variations of recuperator effectiveness, E versus exhaust gas inlet temperature,Tgi in accordance with the test results (mg≈ma).

Fig. 11 states that the total recuperator capacity values increase by the exhaust gas inlet temperatures increase, Fig.12 states that the recuperator effectiveness rates increase by the exhaust gas inlet temperatures increase on condition that $m_g \approx m_a$ and the exhaust gas outlet temperatures and ambient air inlet temperatures are kept constant.

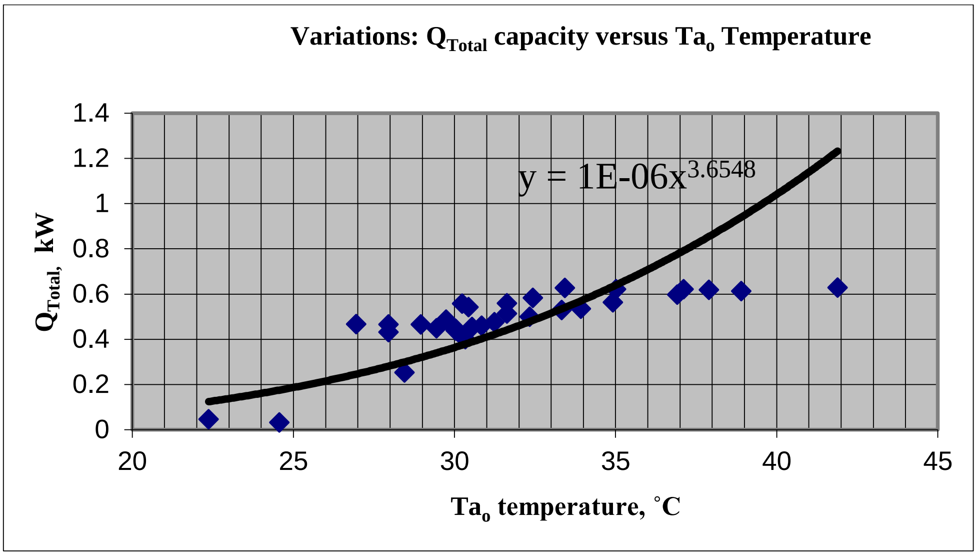


Fig.13. Variations of recuperator capacity, Q_{Total} versus ambient air outlet temperature, Ta_o in accordance with the test results ($m_g \approx m_a$)

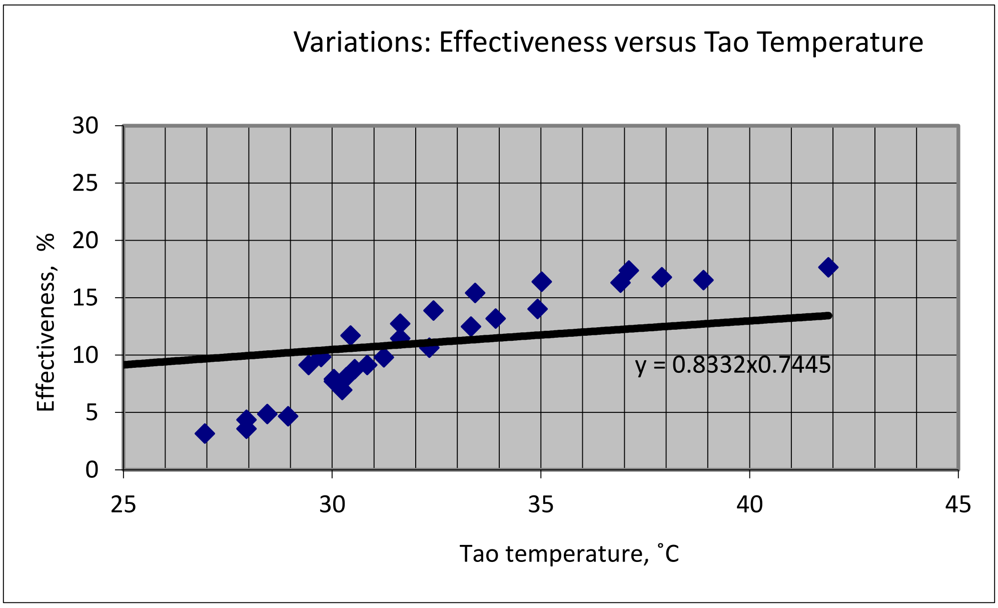


Fig.14. Variations of recuperator effectiveness, E versus ambient air outlet temperature, Ta_o in accordance with the test results ($m_g \approx m_a$).

Fig. 13 states that the total recuperator capacity rates increase by the ambient air outlet temperatures increase, Fig.14 states that the recuperator effectiveness rates increase by the ambient air outlet temperatures increase on condition that $m_g \approx m_a$ and the exhaust gas outlet temperatures and ambient air inlet temperatures are kept constant.

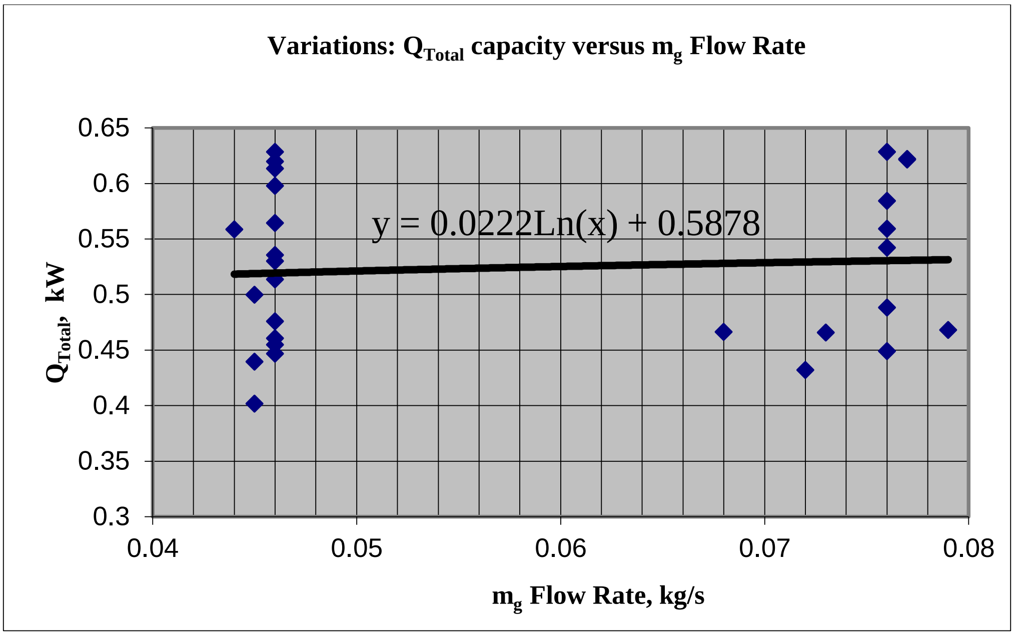


Fig.15. Variations of recuperator capacity, Q_{Total} versus exhaust gas flow rate, m_g in accordance with the test results ($m_g \approx m_a$).

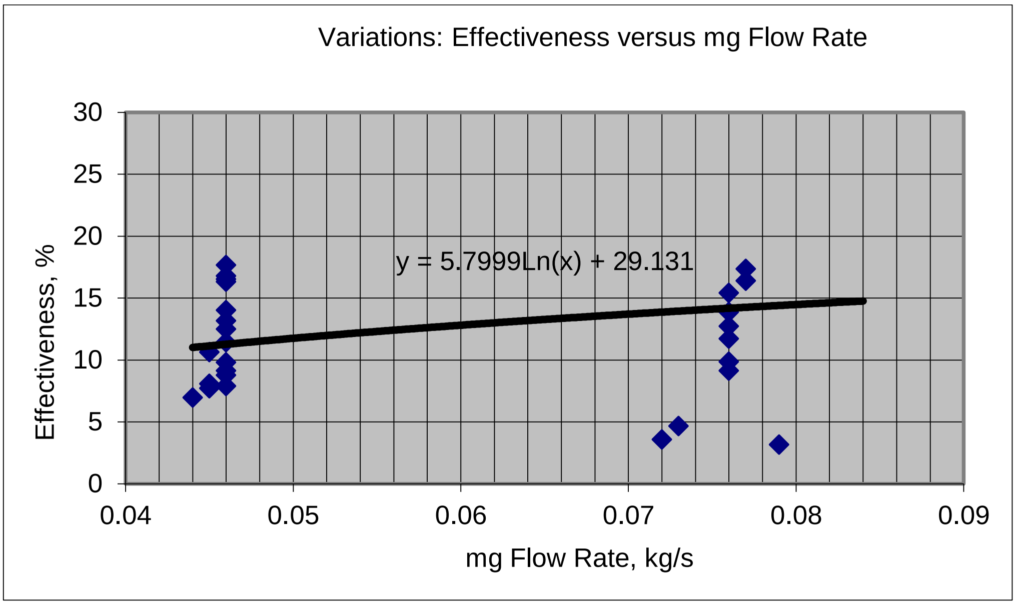


Fig.16. Variations of recuperator effectiveness, E versus exhaust gas flow rate, m_g in accordance with the test results ($m_g \approx m_a$).

Fig.15 states that the total recuperator capacity rates increase by the exhaust gas flow rates increase, Fig. 16 states that the recuperator effectiveness rates increase by the exhaust gas flow rates increase on condition that ma=constant and, the exhaust gas inlet-outlet temperatures and the ambient air outlet temperatures are kept constant.

Thus, under the similar conditions (the exhaust gas inlet-outlet temperatures and the ambient air outlet temperatures are kept constant); if lower ambient air inlet temperatures occur, the exhaust gas flow rates should be increased, ambient air flow rates should be kept constant in order to prevent the decrease of recuperator effectiveness. Another approach of parametric variation can be described as follows: on condition that the exhaust gas inlet-outlet temperatures and the ambient air inlet temperatures are kept constant and the exhaust gas flow rates, total recuperator capacity rates are continuously kept constant, the ambient air outlet temperatures and, so the recuperator effectiveness rates shall increase if the ambient air flow rates decrease.

CONCLUSION

1. In accordance with the general design rule; on condition that mass flow rate of waste exhaust gas is equal to the mass flow rate of ambient air to be heated, and the outlet temperature of waste exhaust gas and inlet temperature of ambient air are constant, as the inlet temperature of waste exhaust gas gets higher the capacity of heat pipe air recuperator also gets higher.
2. On condition that the mass flow rate of exhaust gas is equal to the mass flow rate of ambient air, the outlet temperature of exhaust gas and the inlet temperature of ambient air are constant, if the inlet temperature of exhaust gas gets higher the effectiveness of recuperator also gets higher.
3. As the inlet temperature of exhaust gas approach to the outlet temperature, both the capacity and effectiveness rates of recuperator decrease considerably. Therefore, it is necessary to avoid such an application. That is, the inlet temperature of exhaust gas must not be decreased significantly, in other words, the inlet temperature of exhaust gas must not be approached to the outlet temperature value.
4. In order to keep constant, the capacity rate of recuperator; on condition that the outlet temperature of waste exhaust gas and the inlet temperature of ambient air are constant in any case, if the inlet temperature rates of exhaust gas decrease gradually, both the flow rates of exhaust gas and ambient air must equally be increased.
5. On condition that the outlet temperature of waste exhaust gas and the inlet temperature of ambient air are constant in any case, in order to provide increasing ambient air outlet temperature rates versus decreasing exhaust gas inlet temperature rates, the ambient air flow rates must be decreased and the exhaust gas flow rates must be kept constant. Under these circumstances, the recuperator effectiveness rates shall increase. Such an operating condition is appropriate if ambient air flow rate is required to decrease.
6. On condition that the inlet –outlet temperatures of exhaust gas and the inlet temperature of ambient air are kept constant in any case, in order to provide increasing ambient air outlet temperature rates, the ambient air flow rate must be decreased and exhaust gas flow rate must be kept constant. However, during this application, the decreasing rate of ambient air is not a sharp drop as much introduced by above conclusion-item 5. Therefore, the total capacity rates remain constant and the effectiveness rates increase.
7. If the outlet-inlet temperatures of exhaust gas and the inlet-outlet temperatures of ambient air are always kept constant, and if the flow rates of both exhaust gas and ambient air are equally increased, therefore, the capacity rates increase.
8. If all the temperature rates indicated by above conclusion-item 7 are kept constant at the design values, the maximum flow rates of exhaust gas and ambient air to be used in order to increase the capacity rate, must be equal to the flow rates accepted for design conditions.
9. The most appropriate capacity and effectiveness results for the heat pipe air recuperator are obtained when the operating conditions approach the design values.
10. Due to the reason mentioned by above conclusion-item 9, it is necessary to operate the system by adjusting all the variable parameters of heat pipe air recuperator as much as close, even equal to the design values, in order to provide the most appropriate results.

DATA AVAILABILITY STATEMENT

Data available on request from the author;
The data that support the findings of this study are available from the corresponding author, [Emin Taner ELMAS, ETE], upon reasonable request.
Policy: Basic, Share upon Request.

REFERENCES

1. **Abd El-Baky, M.A., and Mohamed, M.M.,** 2007, Heat Pipe Heat Exchanger for Heat Recovery in Air Conditioning, Applied Thermal Engineering, 27:795-801p.
2. **Abdel-Bary, M., Abdel-Samad, S., and Kilian, K.,** 2005, A Very Light and Thin Liquid Hydrogen/Deuterium Heat Pipe Target for COSY Experiments, Cryogenics, 45:489–495p.
3. **Aghbalou, F., Mimet, A., Badia, F., Illa, J., El Bouardi, A., and Bougard, J.,** 2004, Heat and Mass Transfer During Adsorption of Ammonia in A Cylindrical Adsorbent Bed: Thermal Performance Study of A Combined Parabolic Solar Collector, Water Heat Pipe and Adsorber Generator Assembly, Applied Thermal Engineering, 24: 2537–2555p.
4. **ANSI/AHRI Standard 1060,** 2005, 2005 Standard for Performance Rating of Air-to-Air Exchangers for Energy Recovery Ventilation, U.S.A., 9p.
5. **Bejan, A., and Kraus, A.D.,** 2003, Heat Transfer Handbook, John Wiley & Sons, Inc., New Jersey, 1480p.
6. **Birkholzer, J.T.,** 2006, A Temperature-Profile Method for Estimating Flow in Geologic Heat Pipes, Journal of Contaminant Hydrology, 85:89– 117p.

7. **Boukhanouf, R., Haddad, A., North, M.T., and Buffone, C.,** 2006, Experimental Investigation of A Flat Plate Heat Pipe Performance Using IR Thermal Imaging Camera, Applied Thermal Engineering, 26: 2148–2156p.
8. **Burgess, W.A., Ellenbecker, M.J., and Treitman, R.D.,** 2004, Ventilation for Control of The Work Environment, John Wiley & Sons, Inc., New Jersey, 424p.
9. **Carbajal, G., Sobhan, C.B., Peterson, G.P., Queheillalt, D.T., and Wadley, H.N.G.,** 2006, Thermal Response of A Flat Heat Pipe Sandwich Structure to A Localized Heat Flux, International Journal of Heat and Mass Transfer, 49:4070–4081p.
10. **Çengel, Y.A. and Turner, R.H.,** 2005, Fundamentals of Thermal – Fluid Sciences, The McGraw-Hill Companies, Inc., New York, 1232p.
11. **Çengel, Y.A.,** 2006, Heat and Mass Transfer A Practical Approach, The McGraw-Hill Companies, Inc., Singapore, 879p.
12. **Cheikh, H.B., and Bouchair, A.,** 2004, Passive Cooling by Evapo-Reflective Roof for Hot Dry Climates, Renewable Energy, 29:1877–1886p.
13. **Chi, S. W.**, 1976, Heat Pipe Theory and Practice A Sourcebook, Hemisphere Publishing Corporation, Washington, 241p.
14. **Cui, H., Wang, Z., Guo, Y., Xu, W., and Yuan, X.,** 2006, Thermal Performance Analysis on Unit Tube for Heat Pipe Receiver, Solar Energy, 80:875–882p.
15. **Dobson, R.T.,** 2005, An Open Oscillatory Heat Pipe Water Pump, Applied Thermal Engineering, 25:603-621p.
16. **Dobson, R.T.,** 2004, Theoretical and Experimental Modelling of An Open Oscillatory Heat Pipe Including Gravity, International Journal of Thermal Sciences, 43:113–119p.
17. **Dunn, P. and Reay, D.A.**, 1982, Heat Pipes, Pergamon Pres Ltd., England, 308p.
18. **Dussadee, N., Punsaensri, T., and Kiatsiriroat, T.,** 2007, Temperature Control of Paddy Bulk Storage With Aeration–Thermosyphon Heat Pipe, Energy Conversion and Management, 48:138–145p.
19. **ECA Energy Technology Criteria List 2009,** 2009, Air to Air Energy Recovery, Queens Printer and Controller of HMSO 2009, England, 4p.
20. **Faghri, A.,** 1995, Heat Pipe Science and Technology, Taylor & Francis, Washington, 874p.
21. **Güngör, A., Özbalta, N., ve Gülçağ, M.,** 1995, Isı Borulu Güneş Enerjisi İle Çalışan Hacim Isıtma Amaçlı Bir Konvektörün Geliştirilmesi, Proje No: Misag-22, Tübitak, 110s.
22. **Holley, B., and Faghri, A.,** 2006, Permeability and Effective Pore Radius Measurements for Heat Pipe and Fuel Cell Applications, Applied Thermal Engineering, 26:448-462p.
23. **Holley, B., and Faghri, A.,** 2005, Analysis of Pulsating Heat Pipe With Capillary Wick and Varying Channel Diameter, International Journal of Heat and Mass Transfer, 48:2635–2651p.
24. **Hussein, H.M.S., El-Ghetany, H.H., and Nada, S.A.,** 2006, Performance of Wickless Heat Pipe Flat Plate Solar Collectors Having Different Pipes Cross Sections Geometries and Filling Ratios, Energy Conversion and Management, 47:1539–1549p.
25. **Huang, B.J., Lee, J.P., and Chyng, J.P.,** 2005, Heat-Pipe Enhanced Solar Assisted Heat Pump Water Heater, Solar Energy, 78:375–381p.
26. **Incropera, F.P.**, 1996, Fundamentals of Heat and Mass Transfer, John Wiley & Sons, Inc., New York, 886p.
27. **Kakaç, S.**, 1991, Boilers Evaporators & Condensers, John Wiley & Sons, Inc., New York, 835p.
28. **Kakaç, S., and Liu, H.,** 1998, Heat Exchangers Selection Rating and Thermal Design, CRC Press, Florida, 432p.
29. **Kang, S.W., Wei, W.C., Tsai, S.H., and Yang, S.Y.,** 2006, Experimental Investigation of Silver Nano-Fluid on Heat Pipe Thermal Performance, Applied Thermal Engineering, 26: 2377–2382p.
30. **Katpradit, T., Wongratanaphisan, T., Terdtoon, P., Kamonpet, P., Polchai, A., and Akbarzadeh,** 2005, Correlation to Predict Heat Transfer Characteristics of A Closed End Oscillating Heat Pipe at Critical State, Applied Thermal Engineering, 25:2138-2151p.
31. **Kaya, T., and Goldak, J.,** 2006, Numerical Analysis of Heat and Mass Transfer in the Capillary Structure of A Loop Heat Pipe, International Journal of Heat and Mass Transfer, 49: 3211–3220p.
32. **Kays, W.M., and London, A.L.,** 1984, Compact Heat Exchangers, McGraw-Hill, Inc., U.S.A., 335p.
33. **Kempers, R., Ewing, D., and Ching, C.Y.,** 2006, Effect of Number of Mesh Layers and Fluid Loading on the Performance of Screen Mesh Wicked Heat Pipes, Applied Thermal Engineering ,26:589-595p.
34. **Kern, D.Q. and Kraus, A.D.,** 1972, Extended Surface Heat Transfer, Kingsport Press, Inc., U.S.A., 805p.
35. **Kılkış, B.I.,** 2006, Cost Optimization of A Hybrid HVAC System With Composite Radiant Wall Panels, Applied Thermal Engineering, 26:10-17p.
36. **Koito, Y., Imura, H., Mochizuki, M., Saito, Y., and Torii, S.,** 2006, Numerical Analysis and Experimental Verification on Thermal Fluid Phenomena in A Vapor Chamber, Applied Thermal Engineering, 26:1669-1676p.
37. **Kraus, A.D., Aziz, A., and Welty, J.,** 2001, Extended Surface Heat Transfer, John Wiley & Sons, Inc., New York, 1105p.
38. **Kuppan, T.,** 2000, Heat Exchanger Design Handbook, Marcel Dekker, Inc., New York, 1119p.
39. **Lefevre, F., and Lallemand, M.,** 2006, Coupled Thermal and Hydrodynamic Models of Flat Micro Heat Pipes for the Cooling of Multiple Electronic Components, International Journal of Heat and Mass Transfer, 49:1375–1383p.

40. **Legierski, J., Wiecek, B., and Mey, G.,** 2006, Measurements and Simulations of Transient Characteristics of Heat Pipes, Microelectronics Reliability, 46: 109–115p.
41. **Lin, S., Broadbent, J., and McGlen, R.,** 2005, Numerical Study of Heat Pipe Application in Heat Recovery Systems, Applied Thermal Engineering, 25:127-133p.
42. **Ling, Z.,** 2004, A Study on the New Separate Heat Pipe Refrigerator and Heat Pump, Applied Thermal Engineering, 24: 2737–2745p.
43. **Littwin, D.A., and McCurley, J.,** 1981, Heat Pipe Waste Heat Recovery Boilers, Journal of Heat Recovery Systems, 1(4): 339-348p.
44. **Liu, D., Tang, G., Zhao, F.Y., and Wang, H.Q.,** 2006, Modeling and Experimental Investigation of Looped Separate Heat Pipe as Waste Heat Recovery Facility, Applied Thermal Engineering, 26: 2433–2441p.
45. **Liu, Z., Wang, Z., and Ma, C.,** 2006, An experimental Study on the Heat Transfer Characteristics of A Heat Pipe Heat Exchanger With Latent Heat Storage. Part I: Charging Only Discharging Only Modes, Energy Conversion and Management, 47: 944–966p.
46. **Liu, Z., Wang, Z., and Ma, C.,** 2006, An experimental Study on the Heat Transfer Characteristics of A Heat Pipe Heat Exchanger With Latent Heat Storage.Part II: Simultaneous Charging/Discharging Modes, Energy Conversion and Management, 47: 967–991p.
47. **M&M Metals,** “Heat Pipe Heat Sink Assemblies”, http://www.mmmetals.com/pages/heat_pipe_heat_sinks/heat_pipe_heat_ sink.htm.
48. **Maydanik, Yu.F.,** 2005, Loop Heat Pipes, Applied Thermal Engineering, 25:635-657p.
49. **Mo, Q., and Liang, J.T.,** 2006, A Novel Design and Experimental Study of A Cryogenic Loop Heat Pipe With High Heat Transfer Capability, International Journal of Heat and Mass Transfer, 49:770–776p.
50. **Moon, S.H., Hwang, G., Ko, S.C., and Kim, Y.T.,** 2004, Experimental Study on the Thermal Performance of Micro-Heat Pipe With Cross-Section of Polygon, Microelectronics Reliability, 44:315–321p.
51. **Murer, S., Lybaert, P., Gleton, L., and Sturbois, A.,** 2005, Experimental and Numerical Analysis of The Transient Response of A Miniature Heat Pipe, Applied Thermal Engineering, 25:2566-2577p.
52. **Nadalinia, R., and Bodendieckb, F.,** 2006, The Thermal Control System for A Network Mission on Mars: The experience of the Netlander mission, Acta Astronautica, 58:564-575p.
53. **Niekawa, J., Matsumoto, K., and Koizumi, T.,** 1981, Performance of Revolving Heat Pipes and Application to A Rotary Heat Exchanger, Journal of Heat Recovery Systems, 1(4): 331-338p.
54. **Nilson, R.H., Tchikanda, S.W., Griffiths, S.K., and Martinez, M.J.,** 2006, Steady Evaporating Flow in Rectangular Microchannels, International Journal of Heat and Mass Transfer, 49:1603–1618p.
55. **Noie, S.H.,** 2006, Investigation of Thermal Performance of an Air-to-Air Thermosyphon Heat Exchanger Using e-NTU Method, Applied Thermal Engineering, 26:559-567p.
56. **Osaka Tel ve Maden Sanayi Firma Ürün Kataloğu,** 2007, İstanbul, 16s.
57. **Peterson, G.P.,** 1994, An Introduction to Heat Pipes Modeling Testing and Applications, Wiley-Interscience John Wiley & Sons, Inc., New York, 356p.
58. **Reay, D.A., and Kew, P.A.,** 2006, Heat Pipes Theory Design and Applications, Elsevier Butterworth-Heinemann, Oxford, 377p.
59. **Riehl, R.R., and Dutra, T.,** 2005, Development of An Experimental Loop Heat Pipe for Application in Future Space Missions, Applied Thermal Engineering ,25:101-112p.
60. **Riehl, R.R., and Siqueira, T.C.P.A.,** 2006, Heat Transport Capability and Compensation Chamber Influence in Loop Heat Pipes Performance, Applied Thermal Engineering ,26:1158-1168p.
61. **Riffat, S.B. and Gan, G.,** 1998, Determination of Effectiveness of Heat Pipe Heat Recovery for Naturally Ventilated Buildings, Applied Thermal Engineering, 18:121-130p.
62. **Riffat, S.B., Zhao, X., and Doherty, P.S.,** 2005, Developing A Theoretical Model to Investigate Thermal Performance of A Thin Membrane Heat Pipe Solar Collector, Applied Thermal Engineering, 25:899-915p.
63. **Riffat, S.B., and Zhao, X.,** 2004, A Novel Hybrid Heat Pipe Solar Collector/CHP System—Part 1: System Design and Construction, Renewable Energy, 29:2217–2233p.
64. **Rittidech, S., Dangeton, W., and Soponronnarit, S.,** 2005, Closed-Ended Oscillating Heat-Pipe (CEOHP) Air-Preheater for Energy Thrift in A Dryer, Applied Energy, 81:198-208p.
65. **Rohsenow, W.M., Hartnett, J.P., and Ganic, E.N.,** 1985, Handbook of Heat Transfer Applications, McGraw-Hill, Inc., New York, 960p.
66. **Rojas, M.E., and Andre´s, M.C.,** 2006, Theoretical and Experimental Study of Two-Phase Flow in Micro-Channels Grooved into Horizontal Pipes, International Journal of Multiphase Flow, 32: 517–526p.
67. **Romberga, O., Bodendiecka, F., Blockb, J., Nadalinic, R., and Schneiderd, N.,** 2006, Netlander Thermal Control, Acta Astronautica, 59:946-955p.
68. **Sakulchangsatjatai, P., Terdtoon, P., Wongratanaphisan, T., Kamonpet, P., and Murakami, M.,** 2004, Operation Modeling of Closed-End and Closed-Loop Oscillating Heat Pipes at Normal Operating Condition, Applied Thermal Engineering, 24:995–1008p.

69. **Shah, R.K., and Sekulic, D.P.,** 2003, Fundamentals of Heat Exchanger Design, John Wiley & Sons, Inc., New Jersey, 941p.
70. **Silverstein, C.C.,** 1992, Design and Technology of Heat Pipes for Cooling and Heat Exchange, Hemisphere Publishing Corporation, Washington, 368p.
71. **Song, F., Ewing, D., and Ching, C.Y.,** 2004, Experimental Investigation on The Heat Transfer Characteristics of Axial Rotating Heat Pipes, International Journal of Heat and Mass Transfer, 47:4721–4731p.
72. **Srihajong, N., Ruamrungsri, S., Terdtoon, P., Kamonpet, P., and Ohyama, T.,** 2006, Heat Pipe As a Cooling Mechanism in An Aeroponic System, Applied Thermal Engineering, 26:267-276p.
73. **Suman, B., and Kumar, P.,** 2005, An Analytical Model for Fluid Flow and Heat Transfer in A Micro-Heat Pipe of Polygonal Shape, International Journal of Heat and Mass Transfer, 48:4498–4509p.
74. **Suman, B.,** 2006, A Steady State Model and Maximum Heat Transport Capacity of An Electrohydrodynamically Augmented Micro-Grooved Heat Pipe, International Journal of Heat and Mass Transfer, 49:3957–3967p.
75. **Suman, B., and Hoda, N.,** 2005, Effect of Variations in Thermophysical Properties and Design Parameters on the Performance of A V-Shaped Micro Grooved Heat Pipe, International Journal of Heat and Mass Transfer, 48:2090–2101p.
76. **Suman, B., De, S., and DasGupta, S.,** 2005, Transient Modeling of Micro-Grooved Heat Pipe, International Journal of Heat and Mass Transfer, 48:1633–1646p.
77. **Suman, B., De, S., and DasGupta, S.,** 2005, A Model of the Capillary Limit of A Micro Heat Pipe and Prediction of the Dry-Out Length, International Journal of Heat and Fluid Flow, 26:495–505p.
78. **Tan, B.K., Wong, T.N., and Ooi, K.T.,** 2005, Analytical Effective Length Study of A Flat Plate Heat Pipe Using Point Source Approach, Applied Thermal Engineering, 25:2272-2284p.
79. **Tanaka, H., Nakatake, Y., and Watanabe, K.,** 2004, Parametric Study on A Vertical Multiple-Effect Diffusion-Type Solar Still Coupled With A Heat-Pipe Solar Collector, Desalination, 171:243-255p.
80. **Tanaka, H., Nakatake, Y., and Tanaka, M.,** 2005, Indoor Experiments of the Vertical Multiple-Effect Diffusion-Type Solar Still Coupled With a Heat-Pipe Solar Collector, Desalination, 177:291-302p.
81. **TS EN 308**, 1997, Isı Eşanjörleri – Havadan Havaya ve Atık Gazlardan Isı Kazanımı Cihazlarının Performansının Tayini için Deney Metotları, Türk Standartları Enstitüsü – TSE, Ankara, 12s.
82. **Vasiliev, L.L., and Vasiliev Jr. L.L.,** 2004, The Sorption Heat Pipe-A New Device for Thermal Control and Active Cooling, Superlattices and Microstructures, 35:485–495p.
83. **Vasiliev, L.L.,** 2005, Heat Pipes in Modern Heat Exchangers, Applied Thermal Engineering, 25:1-19p.
84. **Vasiliev, L., and Vasiliev Jr., L.,** 2005, Sorption Heat Pipe- A New Thermal Control Device for Space and Ground Application, International Journal of Heat and Mass Transfer, 48:2464–2472p.
85. **Vlassov, V.V., Sousa, F.L., Takahashi, W.K.,** 2006, Comprehensive Optimization of A Heat Pipe Radiator Assembly Filled With Ammonia or Acetone, International Journal of Heat and Mass Transfer, 49:4584-4595p.
86. **Wang, L.W., Wang, R.Z., Lu, Z.S., and Chen, C.J.,** 2006, Studies on Split Heat Pipe Type Adsorption Ice-Making Test Unit for Fishing Boats: Choice of Heat Pipe Medium and Experiments Under Unsteady Heating Sources, Energy Conversion and Management, 47:2081–2091p.
87. **Williams, R.R., and Harris, D.K.,** 2005, The Heat Transfer Limit of Step-Graded Metal Felt Heat Pipe Wicks, International Journal of Heat and Mass Transfer, 48:293–305p.
88. **Williams, R.R., and Harris, D.K.,** 2006, A Device and Technique to Measure the Heat Transfer Limit of A Planar Heat Pipe Wick, Experimental Thermal and Fluid Science, 30:277-284p.
89. **Xu, J.L., Li, Y.X., and Wong, T.N.,** 2005, High Speed Flow Visualization of A Closed Loop Pulsating Heat Pipe, International Journal of Heat and Mass Transfer, 48: 3338–3351p.
90. **Yongxi, M.A., and Hong, Z.,** 2006, Analysis of Heat Transfer Performance of Oscillating Heat Pipes Based on a Central Composite Design, Chinese J. Chem. Eng., 14(2): 223-228p.
91. **Zhang, H., and Zhuang, J.,** 2003, Research, Development and Industrial Application of Heat Pipe Technology in China, Applied Thermal Engineering, 23:1067–1083p.

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