Development of Economical Viable Vapour Compression Refrigeration Cycle based Domestic Water Heater

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***Abstract* - India's present electricity production is above 164000 MW while the per capita power consumption stood at 612 kWh. Total demand for electricity in India is expected to cross 950,000 MW by 2030 [1]. With fast depleting fuel resources, it is necessary to explore other sources of energy. At the same time, it is also necessary to use the available energy judiciously. It is correctly said that saving electricity mean electricity produced. This paper deals with the development of an economically viable Domestic Water Heater based on Vapour Compression Refrigeration (VCR) cycle and to demonstrate the energy saving potential compared to resistance heating.**

It is well known fact that mechanical heat pump has thermodynamic advantage over electric heating since useful heat available for heating is always greater than work consumed for pumping the heat. While for the electric heaters, the heat available is always less than or equal to work consumed. Therefore it is economically beneficial to use heat rejected in the condenser of VCR system.

A domestic water heater (DWH) of 1 kW heating capacity has been designed, fabricated and tested. For the 1 kW heating capacity, evaporator duty and hence compressor capacity has been evaluated from VCR cycle calculations. Various designs of evaporator and condenser have been reviewed. Helical coil shaped evaporator directly exchanging heat with atmospheric air has been designed. Since it was intended to develop storage type water heater, helical coil shaped condenser brazed outside the water storage tank has been designed. Since the capacity of the VCR system is less, capillary tube has been used as an expansion device which has been sized for the 50 ˚ C condensing temperature and 5 ˚ C evaporating temperature. The VCR cycle based DWH has been tested extensively and heating capacity of about 950 W has been obtained. When compared with conventional storage water heater using electric resistance heater the simple payback period of 2.5 years has been calculated. Reduction in CO2 emission due to lesser power consumption of the DWH is calculated to be 1219 kg per year. Thus VCR cycle based DWH is economically viable and environment friendly compare to conventional electric resistance heater based DWH.

Nomenclature

A *Cross sectional area (m^2)*
Bo *Boiling number = q/ G.hfg*
Co *Convection number = $(1/(x-1))^{0.8} (\rho_v/\rho_l)^{0.5}$*
Cp *Specific heat (J/kg.K)*
d *Diameter of tube (m)*
E *Enhancement factor*
evap *evaporative*
F_{fl} *Fluid-surface parameter*
Fr *Froude number = $G^2/\rho l^2 \cdot g \cdot d$*
G *Mass flux (kg/m2.s)*
g *Acceleration due to gravity (m/s2)*
h *Heat transfer coefficient (W/m2.K)*
h_{fg} *Latent heat of vaporization (J/kg)*
k *Thermal conductivity (W/m.K)*
L *Length of tube (m)*
M *Molecular weight*
Nu *Nusselt number*
p *Pressure (N/m2)*
Pr *Prandtl number*
Q *Heat flux (W/m2)*
Qe *Evaporating heat (W)*
Qc *Condensing heat (W)*
q *Specific heat flux (W/m2.s)*
Re *Reynolds number = G (1-X) d/μl*
S *Suppression factor*
T *Temperature (K)*
x *Quality of refrigerant*
Xtt *Martinelli's coefficient*

Subscripts

cb *convective boiling*
eq *equivalent*
l *Liquid phase*
g or v *Vapour phase*
i *inner*
mc *Microconvective*
nc *Nucleate convection*
pb *pool boiling*
r *reduced*
TP *two phase*
sat *saturation*

Greek letters

α *Thermal expansion coefficient*
γ *Dynamic viscosity (m2/s)*
μ *Viscosity (N.s/m2)*
ρ *Density (kg/m3)*
σ *Surface tension (N/m)*
ψ *Dimensionless parameter (shah)*

Key words: **Energy Saving, Waste heat recovery, Domestic water heater, Green Technology, VCR cycle**

I. INTRODUCTION

Fossil fuels based and less efficient electrical equipments are still being used for heating during the winter season. However, efficient energy utilization is getting importance due to environmental and energy problems such as global warming, ozone depletion and the depletion of fossil fuels resources. In this context, an energy efficient heat pump has been proposed as an economical option to conventional water heater.

Heat pump has thermodynamic advantage over direct electric heating i.e. amount of heat available for the heating purpose is more that electric work supplied compare to electric heater, where heat available for heating purpose is either equal to or less that external work supplied. Thus for the same heating effect, energy consumption of the heat pump is less compared to electric heater.

The objective of the project is to develop economically viable VCR cycle based domestic water heater which will have reasonably good payback period compared to conventional electrical water heaters. Performance of the VCR cycle based domestic water heater has been compared with conventional electric heater in terms of energy consumption and initial cost.

Various hydrodynamic conditions are encountered during evaporation and condensation of refrigerant so; this paper also includes review of different correlations for evaporator and condenser design for calculation heat transfer coefficient. Various design options for evaporator and condenser has been considered. Evaporator may be refrigerant to water or refrigerant to air heat exchanger. When water is used as heat exchange fluid for evaporator, overall heat transfer coefficient will be higher and hence size and cost of evaporator will be lower. But considering the application, it was decided to use air as heat exchange fluid for the evaporator. Since air side heat transfer coefficient is lower, fins may be provided to improve air side heat transfer. The condenser is water to refrigerant heat exchanger. Since it is intended to designed storage type water heater the only design which is of interest is condenser coil wrapped inside or outside the storage tank. From heat transfer view point coil located inside the tank may be better but considering the fouling and maintenance aspect it was decided to provide the coil outside the tank.

1 Correlations for Heat Exchanger Design:

1.1 Boiling Correlations for Evaporator Design:

The evaporator of the DWH is a refrigerant to air heat exchanger in which refrigerant is evaporated while flowing through the evaporator tubes. Therefore various flow boiling heat transfer correlations have been reviewed to evaluate refrigerant side heat transfer coefficient.

The heat transfer coefficients for the flow boiling inside the evaporator can be evaluated from conduction and forced convection in heat transfer theory as given below,

$$\frac{1}{h_r A_i} = \frac{1}{U_o A_O} - \frac{1}{h_a A_o} - \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi k L} \qquad \text{… (1)}$$

Where hr and ha represent the refrigerant side and air side heat transfer coefficients (W/m2°C) respectively, Uo is the overall heat transfer coefficient (W/m2°C), ln(ro/ri)/2πkL denotes wall resistance.

1.1.1 Shah correlation [2] [3]

Shah proposed a correlation where heat transfer coefficient for two phase flow can be evaluated from a ratio of heat transfer coefficient for two phase flow to heat transfer coefficient if only liquid refrigerant is flowing through the tube as given below.

$$\frac{h_{TP}}{h_l} = \psi \qquad \text{... (2)}$$

ψ can be determined from the largest value of ψnb or ψcb.

For horizontal tubes with Frl ≤ 0.04,

$$N = 0.38 * (Fr_l)^{-0.3} \qquad \text{… (3)}$$

For N > 1.0,

$$\psi_{nb} = 1 + 46 B_o^{0.5} \; \textit{For} \; B_o < 0.3\times10^{-4} \qquad \text{... (4)}$$

$$\psi_{nb} = 230 B_o^{0.5} \quad \textit{For} \; B_o > 0.3\times10^{-4} \qquad \text{... (5)}$$

$$\psi_{cb} = \frac{1.8}{N^{0.8}} \qquad \text{... (6)}$$

Where, Boiling number $B_o = Q / h_{fg} \times G$ ... (7)

1.1.2 Kandlikar correlation [2] [3]

Kandlikar [2] [3] also proposed a correlation in terms of the ratio of heat transfer coefficients as given by Shah [2] [3] which is given below.

$$\frac{h_{TP}}{h_l} = C1 * CO^{C2} * (25 * Fr_l)^{C5} + C3 * B_o^{C4} * F_{fl} \qquad \text{… (8)}$$

$$CO = \left(\frac{1-X}{X}\right)^{0.8} * \left(\frac{\rho_v}{\rho_l}\right)^{0.5} \qquad \text{… (9)}$$

Condition	*C1*	*C2*	*C3*	*C4*	*C5*
Co < 0.5	*1.1360*	*-0.9*	*667.2*	*0.7*	*0.3*
Co > 0.5	*0.668*	*-0.02*	*1058*	*0.7*	*0.3*

Dittus-Boelter correlation as given below is to be used to calculate single phase transfer coefficient hl

$$h_l = 0.023 * \left(\frac{G * D_i * (1-X)}{\mu_l}\right)^{0.8} * (\Pr_l)^{0.4} * \left(\frac{k_l}{D_i}\right) \qquad \text{… (10)}$$

$$h_{lo} = 0.023 * \left(\frac{G * D_i}{\mu_l}\right)^{0.8} * (\Pr_l)^{0.4} * \left(\frac{k_l}{D_i}\right) \qquad \text{... (11)}$$

Froude number $Fr_l = m_r^2 / \rho_l^2 \cdot g \cdot d_i$ … (12)

For R22 and R134a the values of Ffl are 2.2 and 1.63 respectively.

1.1.3 Gungor Winterton correlation [4]

Gungor and Winterton gave the correlation for flow boiling in smooth tubes as

$$h_{TP} = E \times h_l + S \times h_{pb} \quad \text{… (13)}$$

Where,

$$E = 1 + 24000 \times B_o^{1.16} + 1.37\left(\frac{1}{X_{tt}}\right)^{0.8} \quad \text{... (14)}$$

$$S = \left[\frac{1}{1 + \left(1.16 \times 10^{-6} \times E^2 \times (\mathrm{Re}_l)^{1.17}\right)}\right] \quad \text{.. (15)}$$

$$h_l = 0.023 \times (\mathrm{Re}_l)^{0.8} \times (\mathrm{Pr}_l)^{0.4} \times \left(\frac{k_l}{d}\right) \quad \text{... (16)}$$

$$h_{pb} = 55 \times (p_r)^{0.12} \times -(\log_{10} p_r)^{-0.55} \times M^{-0.5} \times q^{0.67} \quad \text{… (17)}$$

1.2 Natural Convection Correlations

1.2.1 Churchill and Chu correlation [5]

Churchill and Chu recommended natural convection correlation for wide range of Rayleigh number for horizontal tube as given below.

$$Nu_D = \left(0.60 + \left(\frac{0.387 \times Ra_D^{1/7}}{(1 + \left(\frac{0.559}{\mathrm{Pr}}\right)^{9/16})^{8/27}}\right)\right)^2 \quad \text{… (18)}$$

Where,

Rayleigh number $Ra_L = \dfrac{g \times \beta \times \Delta T \times L^3}{\alpha \times \gamma}$ … (19)

1.2.2 Morgan correlation [5]

Morgan suggested correlation for natural convection over horizontal tubes using constants and Rayleigh number,

$$Nu_D = \frac{h \times D}{k} = C \times Ra_D^{\ n} \quad \text{… (20)}$$

Value of C and n is given below.

Ra_D	C	n
10^{-10}-10^{-2}	0.675	0.058
10^{-2}-10^{2}	1.02	0.148
10^{2}-10^{4}	0.850	0.188
10^{4}-10^{7}	0.480	0.250
10^{7}-101^{2}	0.125	0.333

1.3 Condensation in smooth tubes:

Heat transfer during condensation inside horizontal plain tubes is only considered. Regarding the estimation of the heat transfer coefficient, many empirical correlations are available in the existing literature and their number is constantly growing due to the continuous evolution of the air-conditioning and refrigeration industry.

In the case of condensation inside horizontal tubes, the phase-change process is dominated by vapour shear or gravity forces in such a way that the regime encountered depends on the force controlling the condensation process. Thus, if annular flow is the dominant process, it is because of the high vapour shear but if stratified, wavy or slug flows is found, it is due to gravity forces. It has been observed that in the annular flow regime, the heat transfer coefficient varies with mass velocity, G, vapour quality, x, and saturation temperature during condensation of pure fluids.

1.3.1 Cavallini and Zecchin correlation [6]

The correlation was obtained considering experimental data for R134a & R22 and is the result of the study of the condensation of saturated vapours inside tubes.

$$h_{tp} = \left(\frac{k_f}{D_h}\right) \times 0.05 \times (\mathrm{Pr}_l)^{0.333} \times (\mathrm{Re}_{eq})^{0.8} \quad \text{… (21)}$$

Where the equivalent Reynolds number, Reeq, is defined by

$$\mathrm{Re}_{eq} = \mathrm{Re}_g \times \left(\frac{\mu_g}{\mu_l}\right) \times \left(\frac{\rho_l}{\rho_g}\right)^{0.5} + \mathrm{Re}_l \quad \text{… (22)}$$

1.3.2 Shah correlation [6]

This was developed using experimental data from the condensation of R134a or R22 inside horizontal, vertical, and inclined pipes of different diameters. The correlation proposed defines the heat transfer coefficient as

$$h_{tp} = h_l \left[(1 - X)^{0.8} + \frac{3.8 x^{0.76} (1 - x)^{0.04}}{p_r^{\ 0.38}}\right] \quad \text{… (23)}$$

1.3.3 Dobson and Chatto correlation [6]

Dobson and Chatto derived their correlation using R134a and R22 refrigerant. They observed that the factors which control the flow in the case of condensation inside smooth horizontal tubes are gravity and vapour shear. At low vapour velocities, the effect of gravity prevails and condensate is formed in the upper part of the tube and flows downwards into a liquid pool which advances throughout the tube (which is driven axially) due to vapour push (or flow) and to gravitational forces (or head).

For Re ≤ 1250,

$$Fr_{so} = 0.025 \times (\mathrm{Re}_l)^{1.59} \left[1 + \left(\frac{1.09 \times X_{tt}^{\ 0.034}}{X_{tt}}\right)\right]^{1.5} \left(\frac{1}{Ga}\right)^{0.5} \quad \text{… (24)}$$

And, for Re ≥ 1250,

$$Fr_{so} = 1.26 * (\mathrm{Re}_l)^{1.04} * \left[1 + \left(\frac{1.09 * X_{tt}^{\ 0.034}}{X_{tt}}\right)\right]^{1.5} * \left(\frac{1}{Ga}\right)^{0.5} \quad \text{… (25)}$$

The force-convective and the film-wise components are weighed so the first one is important at the bottom and the second at the top. Then the final expression is

$$Nu = \left(\frac{0.23 \mathrm{Re}_{VO}^{\ 0.12}}{1 + 1.11 \times X_{tt}^{\ 0.50}}\right) * \left(\frac{Ga \times \mathrm{Pr}_l}{Ja_1}\right)^{0.25} + \left[1 - \left(\frac{\theta_1}{\pi}\right)\right] Nu_{forced} \quad \text{… (26)}$$

Where, θ1 the angle subtended from the top of the tube to the liquid level,

$$Nu_{forced} = 0.0195 \times (Re_l)^{0.8} (Pr_l)^{0.4} \phi f(X_{tt}) \quad \ldots (27)$$

$$\phi f(X_{tt}) = \left[1.376 + \frac{C1}{X_{tt}^{C2}}\right]^{0.5} \quad \ldots (28)$$

Condition	C1	C2
$0 < Fr_f \leq 0.7$	$4.172 + 5.48 \times Fr_l$	7.242
$Fr_f > 0.7$	$1.773 - 0.69 \times Fr_l$	1.655

Under annular flow regime, Dobson and Chatto derived a correlation by considering the Travis expression and assuming that the Reynolds number is usually greater than 1125. So the Nusselt number is given by a two-phase multiplier correlation:

$$Nu = 0.023 \times (Re_l)^{0.8} \times (Pr_l)^{0.4} \times \left(1 + \frac{2.22}{X_{tt}^{0.89}}\right) \quad \ldots (29)$$

Natural convection over vertical plate

1.4.1 Churchill and Chu correlation [5]

For natural convection over vertical plate, Churchill and Chu derived the following correlation

$$Nu_D = \left(0.825 + \left(\frac{0.387 * Ra_D^{1/6}}{\left(1 + \left(\frac{0.482}{Pr}\right)^{9/16}\right)^{8/27}}\right)\right)^2 \quad \ldots (30)$$

For better accuracy in laminar flow and RaL<109 they derived,

$$Nu_D = \left(0.68 + \left(\frac{0.387 * Ra_D^{1/4}}{\left(1 + \left(\frac{0.670}{Pr}\right)^{9/16}\right)^{8/27}}\right)\right)^2 \quad \ldots (31)$$

1.4.2 Catton correlation [7]

The correlation proposed by Catton [7], valid for 1 < H/L < 2, 103 < Pr < 105 and 103 < (RaL*Pr/(0.2+Pr)) is given below.

$$Nu_L = 0.18 \times \left(\frac{Pr \times Ra_L}{0.2 + Pr}\right)^{0.29} \quad \ldots (32)$$

II. HEAT EXCHANGER DESIGN AND CAPILLARY SIZING

The VCR cycle based DWH is designed for 1 kW heating capacity using refrigerant R134a with condenser and evaporator temperatures of 50°C and 5°C respectively. The water storage capacity is 25 litres. Considering above parameters mass flow rate (0.005 kg/sec), theoretical COP (4.9) and evaporator capacity (0.234 TR) has been evaluated from VCR cycle calculation. For appropriate correlation heat transfer coefficient for flow boiling, condensation and air side and water side natural convection calculated.

2.1 Design of Evaporator and Condenser

As stated earlier, the evaporator of the DWH is refrigerant to air heat exchanger. Values of flow boiling heat transfer coefficients using Gungor-Winterton, Kandlikar and Shah correlations are calculated as 2296.4, 4499.7 and 4529.1 W/m2K respectively. Air side heat transfer coefficients are calculated to be 4.69 and 4.24 W/m2K using Churchill – Chu and Catton correlations.

Evaporator has been designed considering conservative values of heat transfer coefficients for refrigerant and air. Physical dimensions of the evaporator are given below.

TABLE 1
DIMENSIONS OF EVAPORATOR

Parameter	Dimension
Inner diameter of tube	6.35 mm
Outer diameter of tube	7.42 mm
Length	13.6 m
Overall Diameter of evaporator	0.367 m
Number of turn	11 nos.
Tube pitch	31.7 mm
Height of evaporator	0.375 m

Figure 1 shows view of the evaporator.

Fig. 1 View of Evaporator

The condenser of the DWH is refrigerant to water heat exchanger. Values of condensing heat transfer coefficients using Cavallini- Zecchin and Dobson - Chatto correlations are calculated as 498.1 and 677.5 W/m2K respectively. Water side heat transfer coefficients are calculated to be 21.2 and 19 W/m2K using Churchill - Chu and Morgan correlations.

Condenser has been designed considering conservative values of heat transfer coefficients for refrigerant and water. Physical dimensions of the condenser are given below.

TABLE 2
DIMENSIONS OF CONDENSER

Parameter	Dimension
Inner diameter of tube	6.35 mm
Inner diameter of tube	7.42 mm
Length	14 m
Overall Diameter of condenser	0.30 m
Number of turn	15 nos.
Pitch size between tube	23.7 mm
Overall height of condenser	0.406 m

Figure 2 shows view of the condenser.

Fig. 2 View of Condenser

2.2 Refrigerant selection [8]

Two refrigerants viz. R22 and R134a were considered to be used for the DWH. Some parameters which have been considered for selection of the refrigerant are given below.

TABLE 3
PARAMETERS FOR SELECTION OF REFRIGERANT

Parameters (Unit)	Refrigerants	
	R22	R134a
Cost of refrigerant (Rs/kg)	350	400
Theoretical COP	5.1	4.9
Cost of compressor of 0.25 TR (Rs)	5393	4582
Operating Pressure (MPa)	2.42	1.682
Global warning potential (GWP) [8]	1700	1300
Ozone depletion potential (ODP) [8]	0.05	0

Since dominant heat transfer coefficients are of air and water side respectively in case of evaporator and condenser, the size of the evaporator and condenser calculated were approximately same for both the refrigerant. R134a compressor costs lower than that for R22. Also Global Warming Potential (GWP) and Ozone Depletion Potential (ODP) of R134a are lower compared to R22. Therefore it was decided to use R134a for the DWH.

2.3 Capillary Sizing [9]

Since the capacity of VCR system used for the DWH is small, it was decided to use capillary tube as an expansion device. There are two approaches for the sizing of capillary tube. 1. Isenthalpic expansion as shown line k-a. 2. Adiabatic or Fanno line expansion as shown by line k-b. Here sections have been assumed at temperature interval of 10°C. For Fanno line flow friction inside the capillary tube is considered and enthalpy of refrigerant decreases due to increases in velocity of flowing refrigerant vapour. Total length of capillary tube is calculated to be 1.395 m for 1.27 mm diameter.

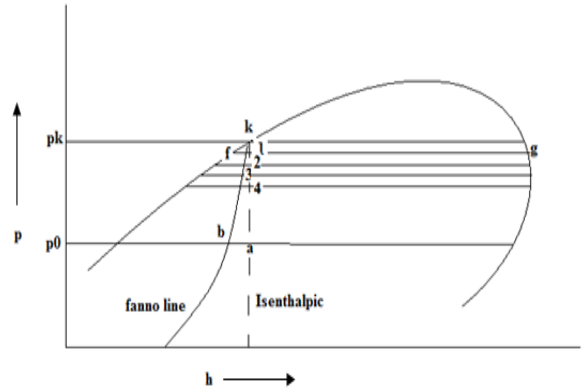

Fig. 3 Incremental Pressure drop in capillary

III. TESTING AND RESULTS

The VCR cycle based DWH has been tested extensively and the results are presented here. Performance of the DWH is compared with conventional electric resistance heater. Simple payback period for the DWH and reduction in CO2 emissions is also calculated.

During various running of the DWH, 25 litres of water was kept inside the condenser. The initial temperature was in the range of 28 to 32°C. Average 30 to 40 minutes were required to raise the temperature of water up to 50°C. Average heating effect calculated was around 950W. Power consumption was measured using energy meter and average power consumption measured was about 251W. Thus average heating COP was calculated to be 3.79.

To evaluate economic and environmental benefits, the VCR cycle based DWH and electric resistance heater based storage water heater of same capacity (1 kW) were tested simultaneously to get water temperature of 50°C. The comparison is shown in Table 3.

TABLE 4
COMPARISON OF VCR CYCLE BASED DWH AND CONVENTIONAL UNIT

Parameters	VCR based DWH	Electrical Resistance Heater
Initial cost of unit (Rs.)	15870	2100

Quantity of water heated (litre)	25	25
Energy consumption (W)	251	990
Total energy consumption /year @ 1500 hr per year (kWh)	376.5	1485
Total energy cost /year (Rs.) @ Rs 5/kWh	1883	7425

Assuming 1500 hr of annual usage, saving of Rs 5542 has been calculated. Since additional investment for VCR cycle based DWH is Rs. 13770, simple payback can be calculated as 2 years and 6 month.

Reduction in CO2 emission from DWH [10]

Most of electricity generation is obtained from coal based thermal power plants in India. For coal based power plant CO2 emission is 800 to 1500 grams per kWh energy production. Using VCR cycle based DWH, annual energy saving of 1108 kWh can be achieved. Considering CO2 emission of 1100 grams per kWh, VCR cycle based DWH can reduce CO2 emission by 1219 kg annually compares to electric resistance heater.

IV. CONCLUSIONS

Various designs of evaporator and condenser have been reviewed. It was decided to design a helical coil shaped evaporator where refrigerant exchanging heat with atmospheric air by natural convection. It was proposed to design and fabricate storage type domestic water heater. Hence, it was decided to design helical coil shaped condenser brazed outside of the storage tank. Thus, water stored inside the storage tank absorbs the heat of condensation by natural convection from vertical wall of the tank. Using the correlations available in literature for flow boiling, condensation and natural convection from vertical wall and natural convection from horizontal tube, the evaporator and condenser were designed. Capillary tube was sized assuming Fanno line flow. Two refrigerants viz. R22 and R134a were considered to be used for the DWH and R134a was evaluated as better option. The VCR cycle based DWH of 1 kW capacity was fabricated and tested extensively to heat the water from room temperature to 50°C.

During testing, actual heating effect and actual COP are calculated to be around 950W and 3.79 respectively. To evaluate economic and environmental benefits, the VCR cycle based DWH and electric resistance heater based storage water heater of same capacity (1 kW) were tested simultaneously to get water temperature of 50°C. The VCR based DWH results in to annual saving of Rs 5542 with additional investment of Rs. 13770 result in to simple payback of 2 year and 6 month. The cost of domestic water heater is calculated to be about Rs. 16000 which can be brought down during mass production. Considering CO2 emission of 1100 grams per kWh, VCR cycle based DWH can reduce CO2 emission by 1219 kg annually compares to electric resistance heater. Thus, VCR cycle based domestic water heater is economically viable and environment friendly option to the electric resistance water heater.

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