Experimental investigation and parameter analysis of LPG refrigeration system using Taguchi method

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Abstract

In this research work, an attempt has been made to study the liquefied petroleum gas (LPG) as an alternative refrigerant to eliminate the global warming potential causes many dangerous impacts on the environment by conventional refrigerants. An LPG refrigeration experimental setup has been fabricated using different lengths of capillary tubes, pressure regulator, evaporator, LPG supply unit, and gas burner. Initially, the parameters working ranges have been confirmed by conducting Exploratory experiments. The evaporator temperature is considered as response parameter which gives the proportionate changes of coefficient of performance. The effects of selected input parameters on evaporated temperature have been investigated. The capillary tube internal diameter, length of capillary tube and system operating time has been selected as input parameters. It was observed from literature survey that there was very few systematic experimentation and statistical analysis were only performed. Thus, L27 Taguchi's design of experiment has been employed to conduct experiments and to identify the significant process parameters. The confirmation test has been conducted to validate the predicted result from the Taguchi method. It was observed that the evaporator temperature has been increased by increasing time of operation and coil diameter of capillary tube. However, the effect on inner diameter is directly proportionate to output response.

Keywords LPG refrigerant · Taguchi method · Capillary tube · Operating time · Evaporator temperature

1 Introduction

Refrigeration is a system in which the heat is removed by application of work such as mechanical, magnetic, laser, thermo-electric and steam. Before the commercial usage of CFC refrigerants, the first generation refrigerants constituted by methyl chloride (CH_3Cl), ammonia, carbon-dioxide, and sulphur dioxide (SO_2). The general characteristic of these refrigerants is highly toxic and corrosive in nature [1]. The second generation refrigerants such as di-chloro-difluoro-methane (R12) and mono-fluoro-tri-chloro-methane (R11) had been invented and used in central air-conditioning plants by Thomas Midgley in 1930s. The second generation refrigerants are then called Chlorofluorocarbon (CFC). Since the 1980s, It was

identified that 1 mol of CFC can deplete 100,000 ozone molecules which cause ozone depletion problem. It was planned to decrease the usage of CFCs and halogens from 80 to 50% during 1999. However, the complete elimination of CFCs has been done during the 2040s' [2]. For eliminating Ozone depletion, the Hydro-fluorocarbons (HFC) refrigerants such as di-fluoro-ethane (HFC-152a), tetra-fluoro-ethane (R-134a) are introduced and it contains hydrogen, chlorine, fluorine, and carbon atoms. However, a carbon-fluorine bond of HFC is one of the strongest bonds in organic chemistry having average bond energy of 420 kJ/kg. The United States Environmental Agency concluded in its annual report saying that due to unregulated use, HFC's could be causing an equivalent amount of global warming as that formed by the release of 10,000

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megatons of carbon-di-oxide per year [3]. Accordingly, the global warming potential of R134a has been estimated to be 1550 tons per 100 years [4]. The USA has also decided to restrict the utilization of R134a starting from 2016. Tetrafluoro-propylene (R1234yf) is used due to same thermo-physical properties as R134a with very low GWP.

In many developing countries, the vapor compression refrigeration system (VCRS) is used with CFC and HFC refrigerants in the home and industrial refrigerating and air-conditioning systems. It retains environmental impacts such as ozone depletion (OD) and global warming (GW) which causes health problems for human and animals. James and Missenden have reported that the possibility of an explosion by the flammability of LPG is a negligible and hydrocarbon charge quantity is only about 50% of the chlorofluorocarbon refrigerants [5]. Bayram Kilic made energy analyses of vapor compression refrigeration cycle with two stages and intercooler using refrigerants like R507, R407c, and R404a. Coefficient of performance, energy efficiency and total irreversibility rate of the system are investigated for various operating conditions [6]. Bukola O Bolaji and Zhongjie Huan studied R22 refrigerant effect and used refrigerant like R290, R600 and R1270 in a vapor compression refrigeration system using the sub-cooling heat exchanger. It was revealed that the saturated vapor pressure and specific volume of R290 and R1270 are very close to R22 and the condenser duty using R290, R600a and R1270 is better than the R22 [7]. Agarwal and Matani studied the performance of different environmentally friendly refrigerants in different proportions. They also observed the effect varying the parameters such as dimensions of the capillary tube, working pressures, and working temperatures [8]. Baskaran and Koshy Mathews (2013) made an analysis of the various eco-friendly refrigerants and compared with R134a to find an alternative replacement. The results showed that RE170, R152a and R600a have a slightly higher performance coefficient (COP) than R134a for the condensation temperature of 50 °C and evaporating temperatures ranging between -30 °C and 10 °C [9]. Kurekci et al. [10] experimentally revealed that COP of alternative refrigerants (HFC134A, HFC404A, HFC407A, HFC410A, and HFC507) was higher than CFC12 and HCFC22. It was investigated that Overall heat transfer coefficient in the evaporator of refrigeration system has been improved by mixing of nanoparticles with R718 refrigerants by Mishra [11]. Hadya et al. [12] explored that the performance parameters like pressure ratio, condensing temperature, discharge temperature of the compressor, power consumption and COP of the system were analyzed using alternate refrigerants like R22, R410A, and R32. Lee and Lee [13] focused on the feasibility of the CO₂ alternative refrigerants and performance characteristics analyzed in automobile vehicles. Ghaderi et al. [14]

attempted ANN approach was used for thermal conductivity prediction in all ranges of density. The thermal conductivity of six refrigerants, R12, R14, R32, R115, R143, and R152 was predicted and the effectiveness of ANN models was compared. Shurooq Talib Ramadhan Al-Hemeri made the experimental and mathematical analysis of condenser and evaporator of the cycle using a test rig for a vapor compression refrigeration system with R-134a as a refrigerant [15]. Very recently, the HCFC refrigerant system was designed and analyzed using R290 (Propane) as a refrigerant by replacing R134a. It was observed that the coefficient of performance of refrigeration systems with R290 as refrigerant is comparable with R134a as a refrigerant and starting torque of compressor reduces which leads to improvement in a life span of the compressor [16].

Maclaine Cross and Leonardi [17] reported that R12 and R134a refrigerants could be replaced by LPG mixtures in car air conditioners. Akash and Salid [18] revealed that the performance of LPG available in the native marketplace (30% propane, 55% butane and 15% iso-butane by percentage of mass) as an alternate to chlorofluorocarbon in a commercial refrigerator. It was concluded that a mass-charge of 80 g gave the best performance. Recently, Gill and Singh [19] attempted that experimental analysis of a vapor compression refrigeration system (VCRS) using the mixture of R134a and LPG with mass fractions of 28:72 as an alternative to R134a. Energy performance of both refrigerants, R134a/LPG (28:72) and R134a were compared under a wide range of experimental conditions. In 2019, LPG mixed TiO₂-based nano-lubricants as a refrigerant experimentally investigated compressor power consumption, cooling capacity, COP, compressor discharge temperature and pressure ratio were taken as process parameters. It was showed, that cooling capacity and COP of the domestic refrigerator using LPG refrigerant with TiO₂ nanoparticles dispersed in a mineral oil lubricant was found to be higher than that of R134a by around 18.74–32.72 and 10.15–61.49%, respectively [20]. The experimental comparative study of LPG with R134a refrigerants in a single evaporator domestic refrigerator has been performed by Fatouh (2006). It was concluded that proposed LPG refrigerator is a long-term candidate to replace the R134a. Setiyo et al. (2017, 2018) attempted some experiments and numerical studies on the effect of cooling characteristics on LPG refrigerants using LPG in various vehicles. It was observed that the higher the evaporator vapor pressure in the evaporator and the greater the mass flow rate of LPG, the greater the cooling effect produced [21–24].

Aforementioned works of literature, very few researchers attempt an experimental investigation and parametric analysis of LPG refrigeration system. However, there was not found any design of experimentation on LPG

refrigerants-based researches. Thus, this research paper is focused on design of experimentation (DoE) of the LPG as an alternative refrigerant to study the performance analysis by conducting systematic experiments using the Taguchi Method.

2 Experimental setup and procedures

The experimental setup contains capillary tubes of different lengths, pressure regulator, evaporator, LPG supply unit, Gas burner, and inlet and outlet pressure gauges as shown in Fig. 1. Liquefied petroleum gas (LPG) comprises 56.4% butane, 24.4% propane, and 17.2% isobutene. The 20 to 50 psi of LPG is supplied to the capillary tube through a pressure regulator. LPG is converted to pressure of 1 psi at capillary tube. The LPG cylinder is equipped with a deep tube that extends to the bottom of the cylinder, before the capillary tube is “liquid state”. Then, low-pressure liquid is passed through an evaporator. While passing low pressure and low-temperature liquid into the evaporator, the heat absorbed from the evaporator chamber can be absorbed by liquid and state of LPG is changed to gas form. The outlet temperature from evaporator can be measured by a thermocouple sensor. The gas will be distributed into a gas burner. Low pressure LPG gas goes into the burner to burns and gas will not be used to store in the LPG cylinder. The 0.7, 0.9 and 1.1 mm size of the capillary tube can be used to

conduct the experiments. The length of the coil may be varied with respect to the inner diameter of the tube. In these experiments, 70, 130 and 190 mm of coil diameter of the capillary tube can be utilized. It was measured from thermocouple T_1 . The outlet temperature of gas measured by thermocouple T_2 as shown in Fig. 1.

3 Experimentation

3.1 Explanatory experimentation

The set of trail experiments have been performed by changing one variable at a time and all other parameters values are kept constant. This method is called one variable at a time (OVAT) method. Initially, the variable reneges could not be predicted to conduct the combined variation of variables. The OVAT results are shown in Fig. 2a–2c.

It was observed that the operating time will decrease the evaporator time while operating long time. Operating time will be considered as a controlling parameter to observe the combined effect with other parameters. However, in this experiments, 10, 30 and 50 min are fixed due to smooth and safe conduction of experiments. The capillary tube outside coil diameter of 70 mm, 130- and 190-mm were considered for quit fitting for fabricated system. The inner diameter of capillary tube is also made by 0.7 mm, 0.9 mm and 1.1 mm for this study.

Fig. 1 Schematic diagram of LPG refrigerator

Fig. 2 **a** Outer coil diameter versus evaporator temperature [constant value: operation time: 30 min and coil inner diameter=0.9 mm]. **b** Inner diameter versus evaporator temperature [Constant value: operation time: 30 min and outer coil diameter=130 mm]. **c** Operating time versus evaporator temperature [constant value: inner diameter=0.9 mm and coil diameter=130 mm]

3.2 Taguchi design of experiments

LPG refrigerator experiments have been conducted based Taguchi L27 orthogonal array. Taguchi design of experiments [DOE] is used to evaluate the effects of input parameters on performance characteristics of this study. As per the guidance of orthogonal array selector, the L27 array was selected for the three input parameters with three-levels [25, 26]. Based on the Taguchi quality design

concept, the values of the control parameters are assigned to the various level of L27 orthogonal array and shown in Table 1. The experiments were conducted in a random manner to avoid bias error [27]. The 27 observations are replicated 3 times to exclude the experimental exceptions [25]. The mean value of every run of DOE has been shown in Table 2. The output temperature can be measured by a digital thermometer and operating time can be recorded by using a stopwatch.

Table 1 LPG refrigerator process parameter and levels

Machining parameter	Symbol	Unit	Level 1	Level 2	Level 3
Inner diameter of capillary tube	d_i	mm	0.7	0.9	1.1
Diameter of capillary tube coil	D	mm	70	130	190
System operating time	t_{op}	Min	10	30	50

Table 2 Experimental design and results using L27 orthogonal array

Exp. no.	Control parameter			Mean value T_{EV}	S/N ratio T_{EV}
	D_i	D	T_{op}		
1.	0.7	70	10	30.0	-29.5424
2.	0.7	70	30	26.1	-28.3328
3.	0.7	70	50	23.3	-27.3471
4.	0.7	130	10	29.0	-29.2480
5.	0.7	130	30	24.1	-27.6403
6.	0.7	130	50	20.1	-26.0639
7.	0.7	190	10	28.2	-29.0050
8.	0.7	190	30	23.4	-27.3843
9.	0.7	190	50	20.8	-26.3613
10.	0.9	70	10	29.1	-29.2779
11.	0.9	70	30	25.2	-28.0280
12.	0.9	70	50	19.9	-25.9771
13.	0.9	130	10	28.4	-29.0664
14.	0.9	130	30	23.2	-27.3098
15.	0.9	130	50	19.1	-25.6207
16.	0.9	190	10	27.1	-28.6594
17.	0.9	190	30	22.1	-26.8878
18.	0.9	190	50	18.4	-25.2964
19.	1.1	70	10	31.0	-29.8272
20.	1.1	70	30	27.3	-28.7233
21.	1.1	70	50	24.4	-27.7478
22.	1.1	130	10	30.1	-29.5713
23.	1.1	130	30	25.3	-28.0624
24.	1.1	130	50	21.5	-26.6488
25.	1.1	190	10	29.3	-29.3374
26.	1.1	190	30	25.1	-27.9935
27.	1.1	190	50	21.2	-26.5267

4 Taguchi analysis

Analysis of variation test is conducted to find the significant level of each process parameters. For this analysis, 95% the confidence level and 5% pure-error (PE) values are selected. The experimental observations of evaporator temperature are further converted into the signal-to-noise (SN) ratio, which is calculated based on the characteristics of the output. Usually, the SN ratio is calculated to find the individual and combined effect of the parameter and the large value is considered as the optimal [9, 10]. In this paper, lower is the better (LB) concept has been applied to maximize the expected response [25]. The SN ratio for the evaporator is calculated as follows.

$$SN_{LB} = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n Y_T^2 \right) \text{dB} \quad (1)$$

where Y_T is the response evaporator temperature and n is number of trail experiments. The 27 set of the SN Ratio of evaporator temperature is shown in Table 2. Figure 2a and b are indicating the SN ratio and Mean effects on output response. It has been revealed that the second level of the capillary tube inner diameter, third level of tube length and third level of operating time are the significant. These best levels of each parameter are considered to predict the optimum response using Minitab Software®.

The confirmation experiments are conducted using optimum levels obtained from the Taguchi approach. The following equation is used to predict the optimal value (μ_{Opt}) of the evaporator temperature [26].

$$\mu_{Opt} = \mu_{tot} + \sum_{i=1}^k [\mu_i - \mu_{tot}] \quad (2)$$

where μ_{tot} —Total mean of the SN ratio; μ_i —Mean SN ratio at the optimal level; k —Number of design variables that affect the response.

The best level of each factors are considered based on higher values of the SN ratio to predict the optimal responses. The evaporator temperature can be minimized by the combination (d_i 2- D 3-top 3) of input factors. The optimum SN ratio for minimum Evaporator temperature ($\mu_{Opt(T_{Ev})}$) can be estimated by using the following equation [25].

$$\mu_{Opt(T_{Ev})} = \mu_{tot} + (\mu_{d_i} - \mu_{tot}) + (\mu_D - \mu_{tot}) + (\mu_t - \mu_{tot}) \quad (3)$$

where μ_{d_i} optimum value of capillary tube inner diameter (Level 2); μ_D optimum value of capillary tube coil diameter (Level 3); μ_t optimum value of operating temperature (Level 3).

The predicted SN ratio would be converted into the optimum mean value of the response by Minitab Software. The minimum of Temperature (18.7037 °C) has obtained with the combination of input parameters of (d_{i2} - D_3 - t_{op3}). The set of confirmation experiments with the best combination of the parameter levels for validating the prediction is shown in Table 3.

5 Results and discussions

Taguchi analysis shows that capillary tube internal diameter, length of the capillary tube and operating time are the significant parameters in order to decrease the evaporator temperature of LPG refrigerator.

It was observed from d_i graph of Fig. 3a and b, the evaporator temperature has getting been reduced by increasing inner diameter of the capillary tube. The small capillary tube will restrict the flow of liquid refrigerants frictional losses of fluid flow with the wetted wall of the tube and high pressure drop. The large diameter of capillary tube has very less pressure drop and it will reduce the cooling effect. Hence, the moderate inner diameter (0.9 mm) of the capillary tube provide sufficient pressure drop with less frictional losses. From Fig. 3a and b of coil diameter (D) graph, the temperature drop of the evaporator is increased while using a large coil diameter of capillary tube due to contact area of refrigerants with outer gas by long travel of gas in the capillary tube. From Fig. 3a and b operating time graph (t_{op}), the operating time of the system will increase the temperature drop of the evaporator system. The work done of system is proportional to the consumption of gases and operating time. The aforementioned conclusions are statistically proved by Taguchi design of experiments. The results of study have been utilized to select the size of the LPG refrigerator components.

6 Conclusions

The eco-friendly LPG refrigerator systematic experiments were conducted using the Taguchi design of experiments to predict best operating parameters for optimum evaporator temperature. The significant effects of the capillary tube internal diameter, length of capillary tube and operating time on evaporator temperature have been investigated. The important observation had been obtained that the moderate inner diameter (second Level: $d_i = 0.9$ mm) of the capillary tube provides

Table 3 Confirmation experiments for Taguchi optimum results

d_i (mm)	D (mm)	T (Min.)	SN ratio (dB)	Pred. T_{evp} (°C)	Exp. T_{evp} (°C)
0.9	190	50	-25.5748	18.7037	18.97

Fig. 3 **a** Effect of process parameters on the SN ratio of evaporator. **b** Effect of process parameters on the mean of evaporator

significant drops of evaporator temperature due to sufficient pressure drop with less frictional losses in the tube. The temperature drop of evaporator has been improved by increasing coil diameter of the capillary tube due to long travel of LPG proportionate to pressure drops. While increasing entire system operating time, evaporator cooling rate will be improved by increasing consumption of fluid. The consumption rate is also proportional to operating time (top) of the system. Thus,

these experimental observations can be used to select the optimum process parameters for providing better cooling in the evaporator.

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Compliance with ethical standards

Conflict of interest The author declares that he has no conflict of interests.

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