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Determination of a Suitable Retrofit of R-134A Using Refrigerant Blends of R290 and R600 Aided by an Optimization Technique

Anaemeje J. C., Owuama K. C., Okafor O. C., Madu K. E.

[1] Chukwuemeka Odumegwu Ojukwu University, Uli Campus, Anambra State, Nigeria;
[2] Grundtvig Polytechnic, Oba, Anambra State, Nigeria

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***Corresponding email:**
okaforobiorac@gmail.com

Abstract. The effect of the hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) refrigerants on the environment through the attack of its halogen contents-chlorine and fluorine, on the ozone layer and the toxic nature of such refrigerants, has paid the attention of researchers to work towards getting suitable alternatives using hydrocarbons (HC) or its blends with HFC refrigerants. This study was centered on getting a suitable retrofit of R-134A with a good coefficient of performance (COP) and low global warming potential (GWP) using the blends of R-290 and R-600 HCs for use in refrigeration systems. An experimental testing rig was developed by assembling various measuring devices to the operational points of a vapor compression refrigerator. A mixture design was developed using the simplex lattice design (SLD) of design expert software 11.0. The response variables considered were COP and GWP. The experimental design was meticulously followed using 1kg for each refrigerant run, and the temperature and pressure values at the operating points were noted. From the results obtained, blend A had the highest COP of 2.5 and the highest GWP value of 3.93. Blend D had the lowest value of C.O.P. of 1.33, while blend B had the lowest value of GWP of 3.51. Also, the optimal blend was achieved at a mixture factor of 59% R-290a and 41% R-600. The response values obtained at this optimal mixture level were COP-2.05182 and GWP – 3.59. Therefore, the optimal blend obtained would be a better retrofit to R-134a and could be used in refrigeration systems.

Keywords: refrigerants, response surface methodology, performance; global warming potential, vapor compression refrigeration system; energy efficiency.

1 Introduction

A refrigeration system is a thermodynamic-based machine that uses a reversed heat engine cycle principle. The reverse heat engine cycle extracts heat energy from the low-temperature region and discharges it to the high-temperature region. The technology of refrigeration has forever caused a considerable improvement in the human standard of living [1]. The invention of refrigerators and air-conditioners has become a priority for comfortable living.

Refrigeration systems can be of any type: ice refrigeration, air refrigeration system, vapor compression, vapor absorption, adsorption, cascade, mixed, vortex tube, thermoelectric, and steam jet refrigeration systems [2].

Vapor compression refrigeration systems are essential from commercial and domestic utility viewpoints. The refrigeration process depends on the refrigerant type employed, among other factors like the compressor, condenser, and operational characteristics. The concern on the refrigerant type used in refrigeration and air conditioning systems resulted from the negative effects caused by the hydrofluorocarbon (HFC) and hydrochlorofluorocarbon (HCFC) refrigerant types on the ozone layer. These refrigerants are responsible for the depletion of the ozone layer that protects the earth from releasing harmful ultraviolet (UV) radiation and cause the global warming effect. The HFCs refrigerants have lower ozone depletion potential (ODP) but higher global warming potential (GWP) value [1]. This concern has thus drifted the attention of researchers to the use of hydrocarbons and their blends as refrigerants [3-5].

R-134a is an HFC refrigerant that is commonly used in most heating, ventilation, and air conditioning (HVAC) and refrigeration systems owing to its favorable characteristics, such as low boiling point, low ignition temperature, zero ozone depletion potential (ODP), solubility in water, non-flammability and critical temperature stability. But this refrigerant is characterized by a very high global warming potential (GWP) value of 1300, hence the need to blend it with hydrocarbons (HC) to reduce its value while maintaining good performance characteristics. Several studies have been conducted using various blends of HCs and blends of HFC-R134a with HCs in search of a suitable retrofit of R-134a.

This study is focused on evaluating the global warming potential and coefficient of performance of R-134a and various mixture designs of R-290 and R-600 using a vapor compression refrigeration system.

The mixture designs of R-290 and R-600 were formulated using the simplex lattice design (SLD) tool and optimized using response surface methodology (RSM).

2 Literature Review

The vapor compression refrigeration system (VCRS) operates based on four distinct processes as shown as in Figure 1 [6].

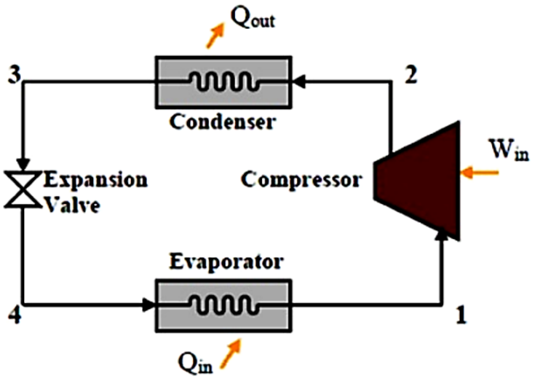

Figure 1 – Process operation of a VCR system [6]

According to [6], the VCR system operation starts with compressing the refrigerant in the compressor device (process 1-2). This process raises the temperature and pressure of the refrigerant so high and then delivers the refrigerant to the condenser (process 2-3) for temperature reduction. The pressure of the refrigerant is reduced in the expansion valve (process 3-4) before the evaporation process that causes the cooling effect (process 4-1). In the quest to get a suitable retrofit of the HCFC and HFC refrigerants, many studies have been carried out in that regard. A study on using R-290 refrigerant as an alternative to R-22 in window air conditioners was carried out by [7].

The results obtained from their study showed that the cooling capacity and energy consumption of R-290 were lower than those of R-22 by 6.6 to 9.7% and 12.4% to 13.5%, respectively. The C.O.P of R-290 was higher than that of R-22 by 2.8% to 7.9%. R-22 and R-290 were analyzed in a 15KW heat pump by [8]. The results showed that R-290 had higher C.O.P. than R-22 by 18%. Also, the C.O.P. of the refrigerant blend of R-290/R-600a and others – R-290, R-1270, R-600, and R-600a, were investigated by [9] in quest of getting an alternative to R-22 used in a heat pump system. The obtained results proved that the cooling and heating capacities of R-290 were smaller and its C.O.P. was slightly higher than that of R-22. The C.O.P. and energy consumption amount of R-134a and that of its various blends of 90/10% for R-134a/R-290 and R-134a/R-600a/R-290 of blend ratio-70/20/10% were studied by [10] in search of a retrofit for R-134a. The study showed that the blend of R-134a/R-290 had the highest C.O.P. The second blend had the least when compared to the base refrigerant, R-134a. He explained that the increase in the C.O.P. of the first blend resulted from the presence of hydrocarbon (HC) in the blend, which caused an increase in the refrigerant’s evaporation rate. Also, the blends of R-134a refrigerant consumed less amount of power than the base refrigerant.

3 Research Methodology

3.1 Materials

The materials used in this study are refrigerants, a vapor compression refrigeration (VCR) system, and other devices coupled to the refrigerator system. The experimental test rig used the refrigerator system to study the refrigerants’ performance modes at different percentage mass compositions according to the experimental design. These materials are discussed.

Thermometers (digital and infrared types) was used to measure the temperature of the refrigerants at various component unit/points. Four thermometers were employed and installed at the inlet and outlet units of the compressor, exit unit of the condenser and exit point of the system’s expansion valve, which was the inlet of the evaporator.

A pressure gauge was used to measure the pressure of the refrigerants at the inlet and exit points of the compressor and at the inlet point of the expansion valve. Therefore, three pressure gauges were used.

A weighing scale was used to measure the compressor’s refrigerant mass for each supply charge.

Vapor compression refrigerator (VCR) system with model number IGNIS 570XL was used to experiment.

Refrigerants, R-134a, and different blends of R-290/R-600 were employed in this study. R-134a was used as the base refrigerant while different percentage mass compositions of R-290 and R-600 were experimented on.

The refrigerants were fed into a gas cylinder and then allowed to flow at a mass flow rate of 0.05 kg/s into the compressor.

The gas charging hose was used to transfer the refrigerant charge from the gas cylinder to the compressor.

A vacuum pump machine was used to vacuum the system.

Design expert 11.0 software package is specialized for two goals – Design of Experiments (DOE) and constructing Response Surface Methodology (RSM). Response surface methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building. By careful design of experiments, the objective is to optimize a response (output variable) that is influenced by several independent variables (input variables). This software tool was used for the experimental design using blends of R290 and R600 as the input variables and coefficient of performance and global warming potential as the response variables to be optimized.

Table 1 shows the functional properties of the refrigerants- the base refrigerant (R-134a) and the HCs blends of R-290 and R-600 used in this study.

Table 1 – Properties of refrigerants [11]

Features	Refrigerant		
	R-134a	R-290	R-600
Chemical formula	CH_2FCH_3	C_3H_8	C_4H_{10}
Appearance	Colourless gas	Colourless gas	Colourless gas
Density, kg/m^3	4.25	2.01	2.51
Molar mass, g/mol	102.03	44.10	58.12
Melting point, °C	–103.3	–187.70	–159.42
Boiling point, °C	–26.3	–42.25	–0.56
ODP	0	0	0
GWP	1300	3.3	4.0

3.2 Experimental setup

The vapor compression refrigeration (VCR) system was used as the testing rig to evaluate the performance of the refrigerants and their blends in quest of finding a good retrofit to R134a with lower global warming potential (GWP) and higher coefficient of performance. Thermometers and pressure gauges were coupled to some units in the refrigerator to evaluate the system's performance while operating on different refrigerant blends. The setup shown in Figure 2 was used for this purpose.

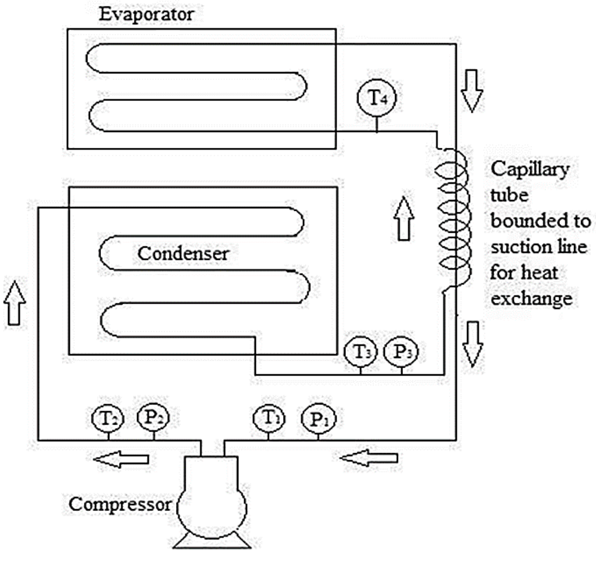

Figure 2 – Schematic diagram of the experimental rig:
T_1 – inlet temperature of the refrigerant at the compressor unit;
T_2 – exit temperature of the refrigerant at the compressor unit;
T_3 – exit temperature of the refrigerant at the condenser unit;
T_4 – inlet temperature of the refrigerant at the evaporator unit;
P_1 – inlet pressure of the refrigerant at the compressor unit;
P_2 – exit pressure of the refrigerant at the compressor unit;
P_3 – exit pressure of the refrigerant at the condenser unit

The method employed in this study stems from the design of the experiment, assembling of the components of the test rig and measurement of the performance parameters of each refrigerant blend, description of the experimental procedures, computation of the global warming potential of each refrigerant blend, computation of the coefficient of performance for each blend, and optimization and analysis of the response variables. These operations are lucidly elucidated.

Design expert software 11.0 was used to perform a mixture design for the two refrigerants- R-290 and R-600. The mixture design, a specialized response surface methodology, employed a simplex lattice design structure in formulating the refrigerant mix using various percentage mass compositions of the refrigerants- R-290 and R-600. The response variables used were: the coefficient of performance and global warming potential. A total of fourteen runs were obtained from the design. The mathematical inequality which governs the mixture design development is given:

$$10 \le \text{R-290} \le 70;\ 30 \le \text{R-600} \le 90 \qquad (1)$$

The schematic diagram of the test rig (Figure 2) was followed in connecting the various measuring instruments and tools to the vapor compression refrigerator components. Thermometers and pressure gauges were installed at the inlet and outlet units of the compressor, exit unit of the condenser and exit point of the expansion valve of the system which was the inlet of the evaporator. These devices noted the temperatures and pressures at those points.

3.3 Experimental procedure

Two gas cylinders were weighed and noted as M_1 and M_2. Then, the required mass of R-290 for the first run was poured into one of the gas cylinders, and the total mass was noted as M_3. Therefore, $M_3 - M_1$ gave us the actual mass of R-290. The mass of R-600 to be mixed with R-290 according to experimental design was transferred to the second gas cylinder with mass M_2 and the mass was noted as M_4. The difference $M_4 - M_2$ gave the required mass of R-600 for blend formulation. The gas charging hose was used to transfer R-600 gas from the second gas cylinder to the first one and was thoroughly shaken to form a good mix. The total mass of the mixture was measured and confirmed to be 1 kg. As discussed, all the measuring tools were connected to the compressor, condenser and evaporator. The gas mixture was transferred to the compressor and the refrigerator was powered. The refrigerant blend was allowed to run for twenty minutes after which the temperature and pressure readings of the VCR components were taken and noted. After noting down the readings, the system was powered off and all the gas in the system was evacuated from the compressor unit using the gas charging hose. The vacuum pump machine was connected to the system to remove any remnant gas mixture in the system completely. This was done to avoid any effect on the result of the initial experiment. These procedures were followed repeatedly for all the various mixture designs of R-290 and R-600 refrigerants.

Figure 3 shows the experimental setup.

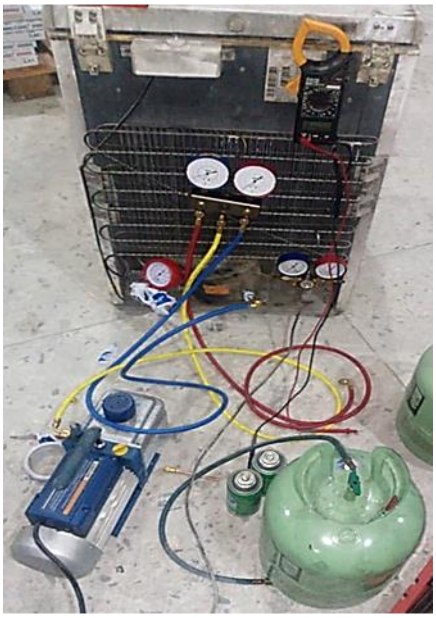

Figure 3 – Experimental setup

3.4 Computational technique

The model for the estimation of the global warming potential (GWP) of refrigerant blends when those of its refrigerants are known was employed by [12]:

$$(GWP_1 \times M_1) + (GWP_2 \times M_2) = (GWP_b) \qquad (2)$$

where $GWP1$ – the global warming potential of refrigerant 1; $GWP2$ – the global warming potential of refrigerant 2, $GWPb$ – the global warming potential of refrigerant blend; M_1 – the percentage mass composition of refrigerant 1 in the blend, %; M_2 – the percentage mass composition of refrigerant 2 in the blend, %.

This model was used to estimate the global warming potential of the various refrigerant blends.

The coefficient of performance of each refrigerant blend was compared with that of the base refrigerant R-134a. As the refrigerant blends have no standard thermodynamic chart as at now, therefore, the values of the operating temperatures and pressures obtained from the experiment were used to evaluate the coefficient of performance of the system using the Carnot cycle efficiency formula employed by [13] and given as follows:

$$\mathrm{C.O.P} = \frac{T_{condenser} - T_{evaporator}}{T_{condenser}}, \qquad (3)$$

where $T_{condenser}$, $T_{evaporator}$ – condenser, and evaporator temperature, respectively, °C; C.O.P – coefficient of performance for the system.

The values of the response variables- coefficient of performance and global warming potential were factored into their respective columns in the simplex lattice design structure. The responses were optimized to get a better retrofit of R-134a that would have lower global warming potential and a high coefficient of performance compared to HFC R-134a refrigerants.

4 Results and Discussion

4.1 Performance characteristics

The result of the performance parameters or response variables used to determine the best refrigerant blend that could serve as a good alternative or retrofit of the HFC, R-134a, is presented in Table 2.

Table 2 – Response performance of R-134a and R-290/R-600 blends

Refrigerants	Global warming potential (GWP)	Coefficient of performance (C.O.P.)
R-134a	1300	2.0
Blend A	3.93	2.5
Blend B	3.51	1.7
Blend C	3.79	1.5
Blend D	3.72	1.3
Blend E	3.65	2.0
Blend F	3.86	1.3
Blend G	3.58	2.0

From Table 2, it could be seen vividly that blend A (10% R-290 and 90% R-600) had the highest global warming potential (GWP) value of 3.93. Blend B (70/30% of R-290/ R-600) had the lowest value of 3.51 global warming potential. The high value of global warming potential observed in blend A could be attributed to the high percentage amount of carbon in R-600 which formed 90% of the mass of the mixture. On the other hand, blends B having the lowest GWP value resulted from the lesser amount of R-600 (30%) present in the mix; as such, the percentage of carbon was reduced in the mixture. The GWP of R-134a from table 2 is 1300. Therefore, the blends showed a better value of GWP than the base refrigerant- R-134a. Also, refrigerant blend A (10% / 90% of R-290/R-600) had the highest value of the coefficient of performance – 2.5 than R-134a and other blends. Refrigerant blends- D and F had the lowest C.O.P value of 1.33. These findings could be attributed to the dissipative heat ability of the refrigerants. Refrigerants with more heat dissipative ability will run through the refrigeration cycle more efficiently than the ones with high heat retentive ability or poor thermal conductivity value.

In addition, the result of the performance characteristics of R-134a and the refrigerant blends concerning their respective operational parameters (temperature and pressure) in the refrigerator's components- compressor, condenser, and evaporator is presented in Table 3.

Table 3 – Operating characteristics of the refrigerants at various components of the refrigerator

Refrigerants (blends)	Mass comp., g		Temperature, °C				Pressure, Psi		
	R290	R600	T_1	T_2	T_3	T_4	P_1	P_2	P_3
R-134a			8	110	5	–5	4	135	35
A	100	900	4	81	2	–3	2	61	21
B	700	300	3	86	3	–2	3	64	18
C	300	700	2	90	4	–2	1	61	24
D	400	600	2	86	3	–1	2	53	16
E	500	500	4	84	2	–2	2	51	26
F	200	800	3	87	3	–1	2	60	23
G	600	400	2	83	3	–3	3	60	20

From Table 3, it could be observed that R-134a had the highest inlet temperature into the compressor (T_1), the highest exit temperature from the compressor (T_2), the highest exit temperature from the condenser unit (T_3), the lowest evaporator temperature (T_4), the highest inlet pressure to the compressor unit (P_1), the highest exit pressure from the compressor unit (P_2) and the highest exit pressure from the condenser unit (P_3). The high exit temperature of the refrigerant (R-134a) further confirmed why R-134a is known to consume much power during its cycle operations [14]. A low evaporator temperature attests to a good coefficient of performance, and R-134a had a good coefficient of performance of 2. In comparison to the blends, blend A had the lowest evaporator temperature. This fact explains why it had the highest coefficient of performance compared to the other blends and R-134a.

The behavioral characteristics of the blends could be seen to vary distinctively, and the quest of getting an optimal blend that would comparatively yield better performance objectives and equally serve as a better retrofit for the HFC, R-134a was obtained through optimization technique using simplex lattice design structure which is a specialized response surface methodology tool enshrined in mixture designs.

4.2 Optimization results

From the numerical optimization, the refrigerant blend with the highest desirability value was selected as the best refrigerant that would serve as a better retrofit to R-134a. The desirability plot is shown in Figure 4.

From Figure 4, the highest desirability value of 0.167 was obtained at a mixture blend of 59% R-290 and 41% R-600. The values of the response variables at the gotten optimal mixture blend are shown in Figures 5 and 6.

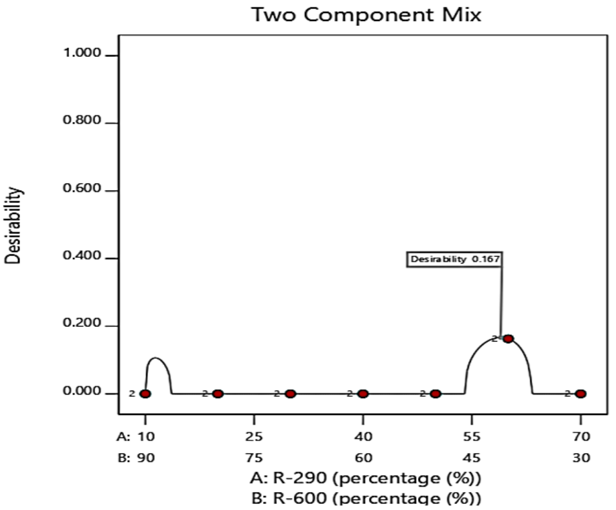

Figure 4 – Desirability of the refrigerant blends

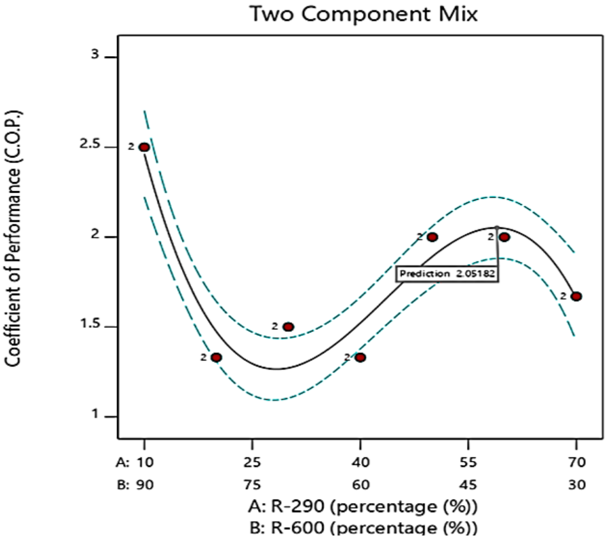

Figure 5 – Coefficient of performance
against the mixture compositions

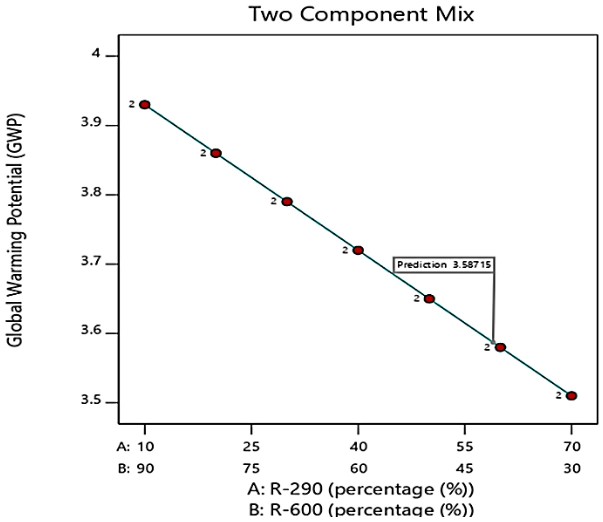

Figure 6 – Global warming potential
against refrigerants mixture compositions

From Figure 5, the coefficient of performance obtained at the optimal blend was 2.05. Blend A with mixture compositions of 10% R-290a, and 90% R-600 had the highest coefficient of performance of value 2.50. The difference in performance coefficient between the optimal blend and blend A is 0.45.

A global warming potential value of 3.59 was obtained for the optimal blend, as shown in Figure 6.

The response predicted values' summary statistics are shown in Table 4 for two-sided confidence of 95%.

Table 4 – Summary statistics of the optimization process

Solution 1 of 2 response	Predicted mean	Predicted median	Standard deviation	SE Pred.	95% PI low	95% PI high
Coefficient of performance (C.O.P.)	2.05	2.05	0.16	0.18	1.66	2.44
Global warming potential (GWP)*	3.59	3.59	–	–	3.59	3.59

Blend B (70% R-290 and 30% R-600) had the lowest global warming potential value of 3.51, while blend A had the highest value of 3.91. The optimal blend which balanced the differences in all the refrigerant blends studied differs by 2.2% from blend B.

5 Conclusions

The numerical optimization gave an optimal blend that balanced the differences/discrepancies in the outputted experimental values of the responses for each refrigerant blend. The optimal blend was achieved at a mixture factor level of 59% R-290a and 41% R-600.The response values obtained at this optimal mixture level were coefficient of performance – 2.05 and global warming potential of 3.59. Therefore, the optimal blend obtained would better retrofit R-134a with a global warming potential of 1300 and a performance coefficient of 2.0.

6 Acknowledgment

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