

## Article

# Modelling of Thermodynamic and Transport Properties of R452B Refrigerant with Low GWP

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**ABSTRACT:** Accurate and reliable estimation of the thermodynamic and transport properties of refrigerants is of paramount importance for the effective design and optimization of refrigeration cycles. In the context of growing environmental concerns, there is a pressing need to transition towards more environmentally benign refrigeration systems and applications. This imperative has driven the search for alternative refrigerants with reduced environmental impact. The refrigerant R452B has emerged as a promising candidate, particularly as a suitable replacement for R410A, due to its favorable thermodynamic characteristics and significantly lower Global Warming Potential (GWP). This research addresses the critical need for precise property data by developing mathematical models for key thermodynamic and transport properties of the R452B refrigerant. Specifically, the study focuses on modelling enthalpy, entropy, specific volume, thermal conductivity, viscosity, and thermal diffusivity. These properties are fundamental to understanding the behavior of the refrigerant within refrigeration systems and are essential for accurate system design and performance prediction. To achieve this modelling objective, the genetic expression programming (GEP) methodology, a powerful evolutionary algorithm capable of automatically generating complex mathematical expressions, was employed. GEP was selected for its ability to discover intricate relationships between variables and to produce explicit equations that can be readily implemented. The accuracy and reliability of the developed GEP models were rigorously evaluated. The coefficient of determination ( $R^2$ ) for the predicted thermodynamic and transport properties across a range of temperatures was found to be between 97% and 99%. This high degree of accuracy demonstrates the robustness and predictive power of the generated equations. The strong correlation between the model predictions and the actual property values indicates that these equations are sufficiently sensitive and accurate to be used with confidence in engineering calculations and simulations. The newly developed mathematical models offer a valuable tool for engineers and researchers working with R452B. These models provide a means to accurately estimate the thermodynamic and transport properties of this refrigerant without the need for complex and time-consuming experimental measurements or computationally intensive simulations. By providing dependable equations, this study facilitates more efficient and accurate design, analysis, and optimization of refrigeration systems utilizing the R452B refrigerant.

**Keywords:** R452B; Low GWP; Thermodynamic properties; Transport properties; Modelling; Genetic programming



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## 1. Introduction

The refrigeration industry has a vital role in the socio-economic of countries. The economic and environmental impact of refrigeration technologies on the world's countries is becoming more important, and this will continue to increase. While refrigeration systems and applications improve living conditions, these technologies also need to be environmentally friendly. The negative environmental impacts of refrigerant using refrigeration technologies, such as global warming and ozone depletion, have been recognized as a major problem. This matter could be achieved with the help of using environment-friendly refrigerants. Fluorochemicals and Hydrochlorofluorocarbons have been phased out due to concerns regarding climate change, high ozone depletion potential (ODP), and global warming potential (GWP), according to the Kyoto Protocol and Montreal Protocol. One such alternative, R452B, has emerged as a promising replacement for R410A due to its lower GWP and comparable thermodynamic properties. R410A, despite its

widespread use in residential heat pumps and air conditioning systems, faces regulatory challenges due to its high environmental impact. R452B offers a lower-GWP alternative with similar efficiency, making it an attractive candidate for existing refrigeration systems with minimal modifications. In addition, the same compressor types, oils, and heat exchangers can be used in systems operating with both refrigerants [1–5].

The modelling of a refrigeration system aims to reach the ideal remedy by reducing the error of a cost function. The refrigeration system modelling is related to the optimization of the energetic parameter [6]. In determining these energy parameters, it is necessary to be accurately knowledgeable of the thermodynamic properties of the refrigerants. Achieving these properties can sometimes be highly difficult and costly for refrigerants.

There are few databases today for the transport properties of refrigerants, such as viscosity and thermal conductivity, required to meet engineering design requirements, and they often contain very high errors due to the difficulty in measuring and the absence of an appropriate theory [7]. Determination of the thermodynamic properties and transport properties are based on functions of temperature and pressure.

Hydrofluorocarbons (HFCs) are still often used in air-conditioning equipment at present. However, they are in the fluorinated greenhouse gas group even though they have ozone-depleting potentials that are zero [8]. R410A refrigerant is still the problem of phasing out because of the high GWP value [9]. R410A is commonly used in residential heat pumps and air conditioning systems because of its high operating pressures, energy efficiency, and cooling capacity. However, R134a is one of the refrigerants that largely contributes to global warming. R452B and R454B are similar in efficiency to R410A and have low GWP values.

Many theoretical and experimental studies have researched alternative refrigerants using low-GWP in refrigeration technology equipment designed for R410A using high-GWP. Saleem and Bradshaw [10] presented a study in which a four-component heat pump model using R410A refrigerant was exercised using R452B and R454A. It was found that the COP increased by as much as 5% with R454B, while R452B had a lower COP compared to R410A during all the simulations. Shen and Ally [11] analyzed the performance of lower-GWP alternative refrigerants R-32, R-452B, R-454B, and R-466A to the R-410A. R-452B and R-454B refrigerants consumed less compressor work while having a similar evaporator heat load to R-410A. In the study, R-454B refrigerant resulted in the highest COP, and R-466A refrigerant resulted in the lowest COP compared to R-410A refrigerant. Devecioğlu [12] compared the refrigerants with low GWP values, namely R446A, R447A, R452B, and R454B, that could be used instead of R410A based on their seasonal energy efficiency ratio and seasonal coefficient of performance values. The SCOP results of R452B and R454B refrigerants are very close to the seasonal coefficient of performance value of R410A. R446A refrigerant has the lowest energy consumption, while R454B refrigerant has the lowest annual energy consumption for heating. Consequently, the R452B refrigerant is the most suitable, with a 3.92 seasonal coefficient of performance value among the alternative refrigerants. Sieres et al. [13] studied the drop-in performance of refrigerants R452B and R454B in an R410A in a heat pump. R452B refrigerant indicated better the compressor's electric power performance than R410A, but worse in terms of COP. R454B refrigerant showed similar COP values compared with R410A refrigerant. Hsu et al. [8] investigated the heat transfer performance of the falling film evaporation and pool boiling of the refrigerants, namely R452B and R454B, instead of R410A. The heat transfer coefficient in falling film mode is inferior to that of pool boiling for the three refrigerants, R410A, R452B, and R454B. The empirical correlation was established based on near-azeotropic fluids' falling film test data. Heredia-Aricapa et al. [14] analyzed the new refrigerant mixtures (HFC/HFO/HC/R744) alternatives to substitute R134a, R404A, and R410A in their different refrigeration and air conditioning systems considering their classification and selection criteria concerning their thermodynamic and physical properties. Panato et al. [15] developed an experimental setup and evaluated the efficiency of a refrigeration system with evaporation temperatures between  $-5$  and  $5$  °C for the R410A refrigerant. The study indicated that alternative refrigerants have lower performance than the R410A refrigerant with energy efficiency, but they have lower GWP than they had a lower environmental impact. There have also been studies using artificial intelligence methods to predict different properties of refrigerants. Dikmen [16] predicted the temperature-pressure relationship of R466A in the saturated liquid-vapor phase and its enthalpy-entropy relationship in the superheated vapor phase using linear regression, artificial neural network and gene expression programming models. Gao et al. [17] used feedforward Artificial Neural Networks (ANN) to calculate isobaric heat capacities of pure HFC and HFO liquid refrigerants. Yılmaz et al. [18] determined the thermodynamic properties such as enthalpy, entropy and specific volume of hydrocarbon refrigerants using the neural network (NN) method. The hydrocarbon (HC) refrigerants used in the study are butane, ethane, methane and propane. Kang et al. [19] presented an approach to the prediction of the viscosity of refrigerant blends based on a modified QSPR method for the estimation of binary interaction parameters and entropy scaling. He et al. [20] presented an attention mechanism enhanced integrated

prediction model for the molecular weight, boiling point, critical temperature and critical pressure of fluorine/chlorine-based refrigerants. The model uses molecular groups as molecular structure descriptors and employs a machine learning algorithm with attention mechanisms. Using the data mining method, Yildirim and Şahin [21] estimated the thermodynamic properties of the new generation R471A refrigerant, such as enthalpy (h) and entropy (s). A simple correlation to describe the temperature and pressure dependence of the liquid dynamic viscosity of low GWP refrigerants, namely hydrofluoro olefins (HFOs) and hydrochlorofluoro olefins (HCFOs), was presented by Tomassetti et al. [22]. Pençe et al. [23] used polynomial regression and GradientBoosting, XGBR, KNNRegressor, and Decision Tree as machine learning algorithms to estimate the thermodynamic properties of R513A refrigerants such as temperature, pressure, enthalpy, and entropy. Li and Baghban [24] introduced a new model for the precise estimation of densities across 48 refrigerant systems, spanning five distinct categories: Hydrofluoroethers (HFEs), Hydrochlorofluorocarbons (HCFCs), Perfluoroalkylalkanes (PFAAs), Hydrofluorocarbons (HFCs), and Perfluoroalkanes (PFAs). The model incorporated a comprehensive set of input variables, including pressure, temperature, molecular weight, and structural groups. The study evaluated the effectiveness of both multilayer perceptron artificial neural network (MLP-ANN) and adaptive neuro-fuzzy inference system (ANFIS) techniques in developing an accurate predictive model. Pierantozzi et al. [25] developed a neural network designed to compute the liquid thermal conductivity of diverse low-GWP refrigerants. Specifically, a feed-forward network algorithm utilizing 5 input parameters (reduced temperature, critical pressure, acentric factor, molecular weight, and reduced pressure) and a single hidden layer was applied to an extensive dataset of 3404 experimental data points for 7 halogenated alkene refrigerants. Rathod et al. [26] trained and compared five regression machine learning (ML) algorithms to evaluate their predictive abilities in replicating the thermodynamic and transport properties of both alkanes and refrigerants. They also analyzed the pairwise correlation between the input features, which encompassed molecular structural details for alkanes and, the count of distinct atoms for refrigerants, and various thermophysical properties. The ML models employed for prediction were random forest regression, decision tree regression, feedforward neural network, multiple linear regression, and polynomial regression. Devotta et al. [27] utilized Artificial Neural Network (ANN) and Random Forest (RF) techniques to predict the flammability class of refrigerants based on their molecular composition and structure. Both the ANN and RF models successfully predicted the flammability classifications for 179 refrigerants with high accuracy.

From the literature research given above, it can be seen that R452B refrigerant is suitable to replace R410A and is also environmentally friendly with its low GWP value. As seen in Table 1, the R452B refrigerant has comparable features comparably thermodynamic qualities with R410A. Thus, these refrigerants could be used in the present refrigeration systems without the need to require significant alterations to the old systems.

**Table 1.** Physical properties of the considered refrigerants [28].

Fluid	Composition (ww <sup>-1</sup> )	Molecular Weight (kgkmol <sup>-1</sup> )	GWP	Critical Temperature (°C)	Critical Pressure (bar)	Boiling Temperature (°C)	Refrigerant Type	Safety Class	Replaces
R-410A	50% R-125/50% R-32	72.6	2088	71.3	49	−60.6	Blend	A1	CFC R-22
R-452B	67% R-32/7% R-125 /26% R-1234yf	63.5	675	77.1	55	−51	Zeotropic blend	A2L	R-410A

The accurate determination of thermodynamic and transport properties is critical for optimizing refrigeration cycle efficiency. These properties influence system performance, energy consumption, and overall sustainability. Traditional methods of determining these properties, including experimental measurements and empirical correlations, can be time-consuming and costly. As an alternative, machine learning and computational intelligence methods such as genetic programming (GEP) have gained popularity in predictive modelling.

The aim of this study is to develop a new, highly accurate, and precise model for the thermodynamic and transport properties of R452B, a 21st-century fluid that can be used as an alternative to R410A. The present study utilized the GEP model. The GEP model constitutes a novel approach to modelling complex, highly non-linear dynamic systems. No literature has been found that estimates the thermodynamic and transport properties of the R452B refrigerant using the GEP model. The new formulations obtained from the GEP model can be used to easily predict the thermodynamic and transport properties of R452B refrigerant. These properties can be determined by the proposed method without the need for any program or software. Consequently, the thermodynamic and heat transfer analysis of refrigeration and air conditioning systems can be considerably simplified.

## 2. Model Method

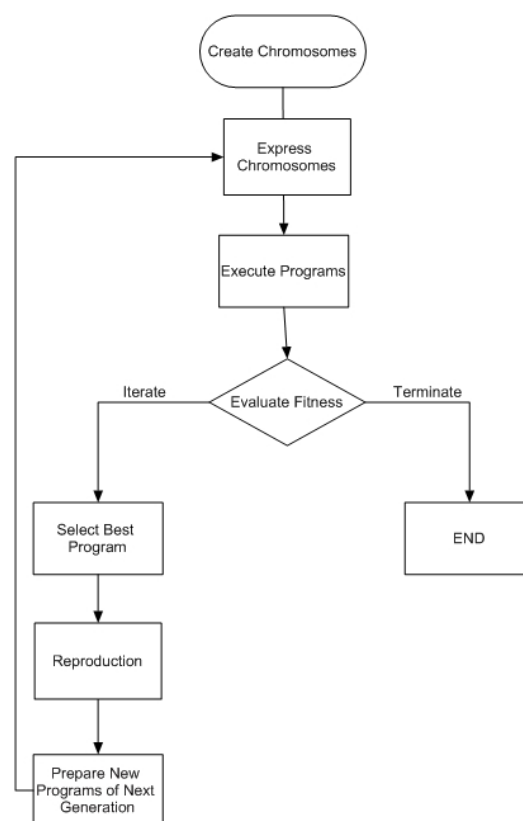
In this study, the GEP model is utilized for calculating R452B refrigerant thermodynamic and transport properties. In the model, the refrigerants were used in saturated (liquid and vapor) regions.

### 2.1. An Overview of the GEP

GEP is an evolutionary algorithm that can model complex non-linear relationships. Traditional linear regression models assume a linear relationship and lack the flexibility of GEP. The Genetic Expression Programming (GEP) method also offers significant advantages over conventional artificial intelligence (AI) approaches due to its superior robustness. Unlike older AI techniques, GEP doesn't easily falter with minor input variations or reasonable noise. Furthermore, its remarkably simple genetic operations provide a key benefit for solving complex problems. These straightforward and efficient characteristics have made GEP a popular and widely adopted method for evolutionary modelling. GEP combines the advantages of genetic algorithms and genetic programming. It employs encoded individuals, represented as genomes, which evolve over multiple generations to optimize a fitness function. The methodology follows these key steps [29]:

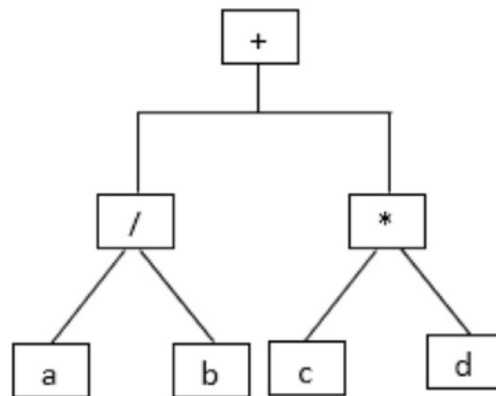
1. Initialization: A population of random expressions is generated.
2. Fitness Evaluation: Each expression is evaluated based on its ability to predict the target properties.
3. Selection and Genetic Operations: The best-performing individuals undergo replication, mutation, and recombination.
4. Iteration: The process continues until convergence is achieved or a predefined performance threshold is met.

Genetic expression programming is a genetic algorithm that uses populations of individuals. GEP uses individuals coded as genomes or chromosomes as an artificial life system. The flowchart of GEP is shown in Figure 1. In a gene expression algorithm, the flow starts with the create chromosomes of the initial population. After the fitness of each individual is evaluated, the individuals are selected according to fitness to reproduce. The reproduction process takes place with stages a replication, a mutation that can occur anywhere in the chromosome, IS (Insertion Sequence) and RIS (Repeated Insertion Sequence) transpositions that are a remnant of the developmental process of the GEP, gene transposition, and gene recombination, respectively. The process is repeated until the best solution has been found [29].



**Figure 1.** The flowchart of a GEP model [29].

In Gene Expression Programming (GEP), the core components are chromosomes (or genomes) and expression trees (ETs). A chromosome is a linear sequence of symbols with a fixed length comprising one or more genes. Interestingly, despite their fixed length, GEP chromosomes can encode structures of varying shapes and sizes. These chromosomes are generated by randomly combining terminals and functions. Each gene within a chromosome represents a sub-expression tree (sub-ET), and these sub-ETs are then linked together by specific linking functions (e.g., +, −, \*, /, √, exp, ln, sin, cos, tanh). For instance, Figure 2 in the original source would typically illustrate how an arithmetic expression like  $(a/b) + (c*d)$  is represented as an expression tree. Further details on GEP can be found in references [30–35].



**Figure 2.** Expression tree of an arithmetical expression.

## 2.2. Data Range and Variables of Refrigerants

A reliable dataset is crucial for training predictive models. In this study, the dataset for the thermodynamic and transport properties of R452B was obtained from Genetron v1.4.2 software [36]. The dataset included:

Thermodynamic properties: Enthalpy (h), entropy (s), specific volume (v).

Transport properties: Thermal conductivity (k), viscosity ( $\mu$ ), thermal diffusivity ( $\alpha$ ).

Temperature was selected as the primary input variable, as refrigerant properties vary significantly with temperature. The pressure was held constant in the saturated region.

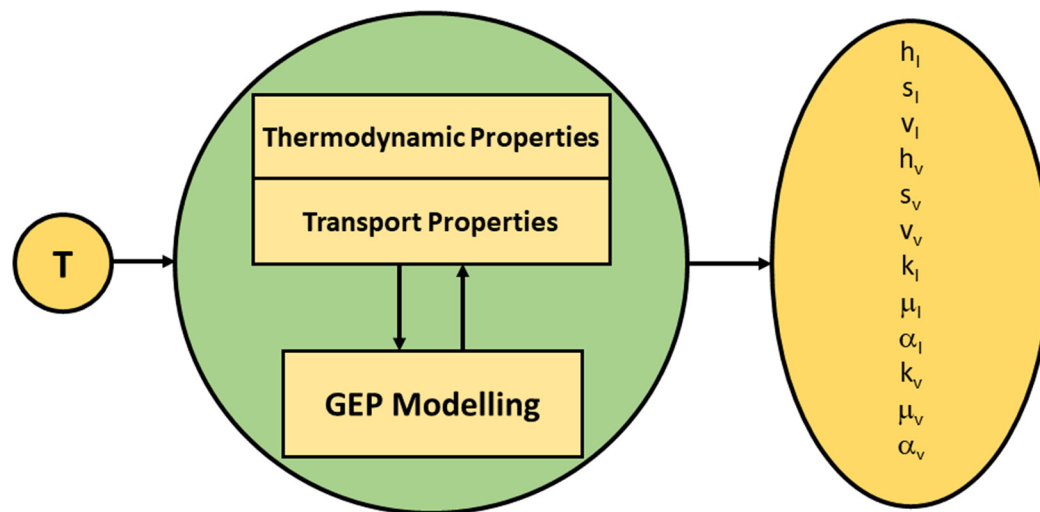
Machine learning algorithms need a dataset with compatible data to train. It is important to provide reliable and accurate data. In this study, the dataset of the considered refrigerant is provided from the Genetron software. The data includes enthalpy ( $\text{kJ kg}^{-1}$ ), entropy ( $\text{kJ kg}^{-1} \text{K}^{-1}$ ), specific volume ( $\text{m}^3 \text{kg}^{-1}$ ), thermal conductivity ( $\text{W m}^{-1} \text{K}^{-1}$ ), Viscosity ( $\text{Pa s}$ ), and thermal diffusivity [ $\text{m}^2 \text{s}^{-1}$ ] of considered refrigerant (Figure 3). The next step in proceeding with a model is a description of independent variables as inputs. Temperature is a variable parameter in the saturated region for considered refrigerant. The functionality relation of properties for R452B refrigerant may be presented as follows:

In saturation region:

$$\text{Thermodynamic properties (h, s, v)} = f(T_i)$$

$$\text{Transport properties (k, } \mu, \alpha) = f(T_i)$$

where h, s, v, k,  $\mu$ ,  $\alpha$ , T shows enthalpy, entropy, specific volume, thermal conductivity, viscosity, thermal diffusivity, and temperature of considered refrigerant, respectively.



**Figure 3.** Modelling diagram of R452B refrigerant.

### 3. Modeling of Thermodynamic and Transport Properties of R452B

We utilized the GEP model for calculating the R452B refrigerant's thermodynamic and transport properties. The enthalpy ( $h$ ), entropy ( $s$ ), specific volume ( $v$ ), thermal conductivity ( $k$ ), viscosity ( $\mu$ ), thermal diffusivity ( $\alpha$ ) values of the liquid (f) and vapor phases (g) of the refrigerant was estimated depending on the temperature ( $T$ ) values. The thermodynamic and transport property data set for the refrigerant was obtained from Genetron software [36]. This dataset has been randomly divided into training and testing sets. In order to find the perfect topology, different GEP parameters (generation, chromosomes, and genes numbers, linking functions, mutation rate, *etc.*) were used. GEP modelling thermodynamic and transport properties of R452B refrigerant realized by using GenEx 5 software [37]. Thermodynamic properties and transport properties for the specified temperature range in saturated regions. The newly developed mathematical correlations from the GEP model can be used in an application range for R452B refrigerant according to the needs of an engineer.

#### 3.1. Model Evaluation of Fundamental Thermodynamic and Transport Parameters

In this work, the GEP model was employed to determine the thermodynamic and transport properties of the R452B refrigerant in both its saturated liquid and vapor states. To identify the most accurate correlation, different GEP parameters were systematically investigated. The resulting optimum GEP correlations for predicting the thermodynamic and transport properties of R452B can be found in Table 2. The best fit non-linear correlations are used to predict the thermodynamic and transport properties of the considered refrigerant. Model selection is based on simplicity and accuracy in the developed model combinations according to the trial and error approach. The GEP models were developed using a specialized software platform with the goal of deriving the correlations for each property. Table 2 shows the formulations of the thermodynamic and transport properties, namely enthalpy, entropy, specific volume, thermal conductivity, viscosity, and thermal diffusivity, for a specified temperature range. The developed correlations are applicable to the saturated liquid and vapor regions of R452B for temperatures between  $-30\text{ }^{\circ}\text{C}$  and  $76\text{ }^{\circ}\text{C}$ .

**Table 2.** Formulas for thermodynamic and transport properties of the R452B refrigerant derived from the GEP model.

		Property	Formulations
Thermodynamic Properties		Saturated liquid enthalpy [kJ kg <sup>-1</sup> ]	$h_l = 200.68 - 2.07 * \sqrt[3]{T} + 2 * T$
		Saturated liquid entropy [kJ kg <sup>-1</sup> K <sup>-1</sup> ]	$s_l = \text{Exp}(0.0055 * T) - 0.0081$
		Saturated liquid specific volume [m <sup>3</sup> kg <sup>-1</sup> ]	$v_l = 10^{-4} \left( 9.36 + \frac{4.54 * T - 25.38}{3.54(83.097 - T)} \right)$
		Saturated vapor enthalpy [kJ kg <sup>-1</sup> ]	$h_v = 442.49 + \exp[1 - \sin(\text{atan}(T - 2.35) + 9.5 * T)] + (\text{atan}(62.33 - T) * 1.52) + [\text{Ln}( -0.78 * T + 12.65 ) * \exp(\text{atan}(T))]$
		Saturated vapor entropy [kJ kg <sup>-1</sup> K <sup>-1</sup> ]	$s_v = \tanh \left[ \left( \sqrt[3]{T} - 89.7 + 1.28 \right)^2 \right] + \sqrt[3]{\tanh(0.237 + 0.98T)}$
		Saturated vapor specific volume [m <sup>3</sup> kg <sup>-1</sup> ]	$v_v = 10^{-3} \left( \frac{1.8}{\sin \left( 10^{\cos(\sqrt[3]{10.1+T})} \right)} + \exp \left[ 1 - \left( \sqrt[3]{(T - 16.35) + \frac{1.69}{T}} \right) \right] \right)$
		Saturated liquid thermal conductivity [W m <sup>-1</sup> K <sup>-1</sup> ]	$k_l = 0.12 - 0.00056[(\sqrt[3]{T} * 1.15) + (T + 3.39)]$
Transport Properties		Saturated liquid viscosity [Pa s]	$\mu_l = 10^{-6}[143.49 + 1.5 * (7.86 - T)]$
		Saturated liquid thermal diffusivity[m <sup>2</sup> s <sup>-1</sup> ]	$\alpha_l = 10^{-7} \left[ 1 - \exp \left( \frac{\frac{T - 9.14}{2} - 39.1}{36.14} \right) \right]$
		Saturated vapor thermal conductivity [W m <sup>-1</sup> K <sup>-1</sup> ]	$k_v = 10^{-4} \left( \sqrt[3]{\frac{T - 68.03}{2}} * (T - 3.39) \right) + \left( \sqrt[3]{-161.97 * (T - 10) + 99.73 + (4.96 * T)} \right)$
		Saturated vapor viscosity [Pa s]	$\mu_v = 10^{-6} \left[ \frac{T}{\left( \text{Ln} \left( \frac{T}{1.4} + 38.4 \right) \right)^2} + 11.23 + \frac{(-22.06 - T)^2}{1668.46} \right]$
		Saturated vapor thermal diffusivity[m <sup>2</sup> s <sup>-1</sup> ]	$\alpha_v = 10^{-7} \left[ \exp(\text{atan}(-17.54 - T)) - \sqrt[3]{T} - 0.148 + \frac{8.32 + \tanh(9.36 * T)}{2} \right]$

### 3.2. Accuracy Assessment of Developed Mathematical Equations

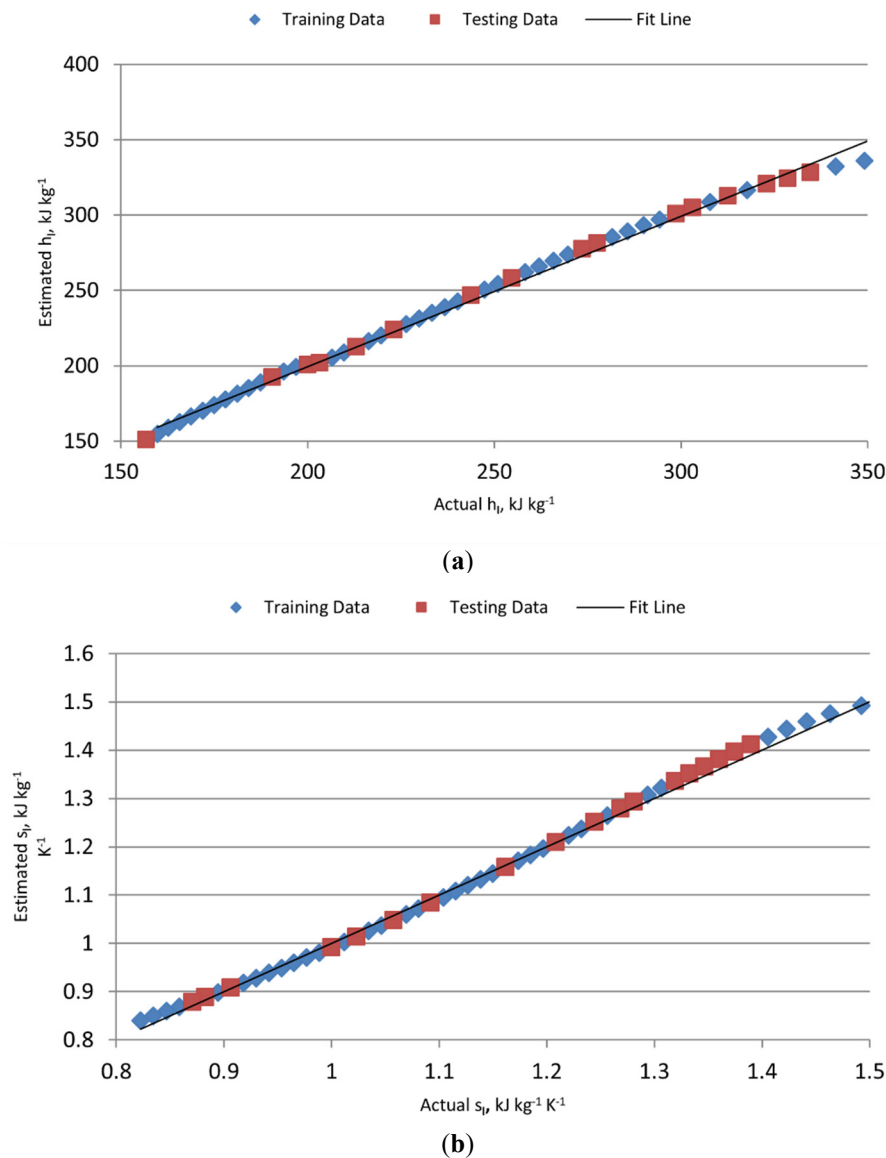
We compared the thermodynamic properties calculated using the formulations obtained from the GEP model with the actual thermodynamic and transport properties obtained from the Genetron software. The performance of GEP correlations was determined using several evaluation criteria: coefficient of determination ( $R^2$ ) and root mean square error (RMSE).

$$R^2 = \left[ \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \right]^2 \quad (1)$$

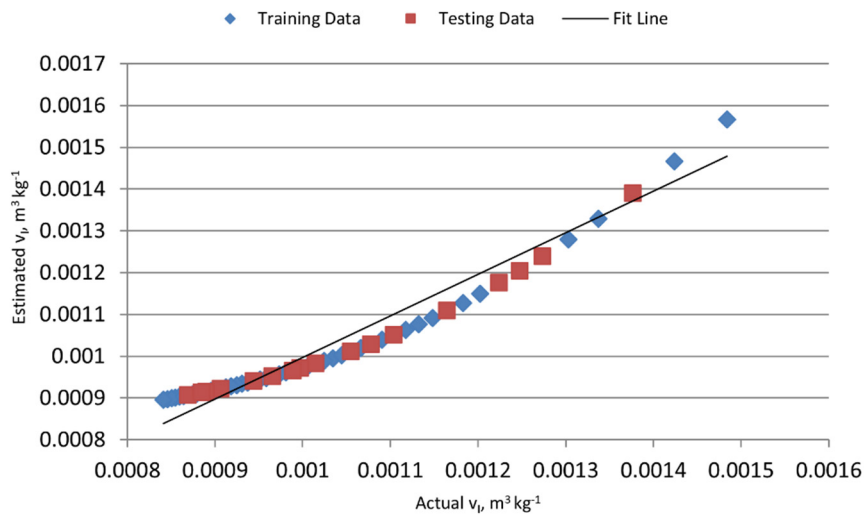
$$\text{RMSE} = \sqrt{\sum_{i=1}^n \frac{(x_i - y_i)^2}{n}} \quad (2)$$

where  $x_i$  and  $y_i$  present the target value and predicted one;  $\bar{x}$  and  $\bar{y}$  indicates mean values at  $x_i$  and  $y_i$ , respectively.  $n$  presents the number of the total number of data.

Figures 4 and 5 show how the actual and predicted thermodynamic properties, namely enthalpy, entropy, and specific volume, in the saturated liquid and saturated vapor region, varied for the different temperature values varied from  $-30$  °C to  $76$  °C. The thermodynamic properties values were predicted with a range of 97% and 99% accuracy.

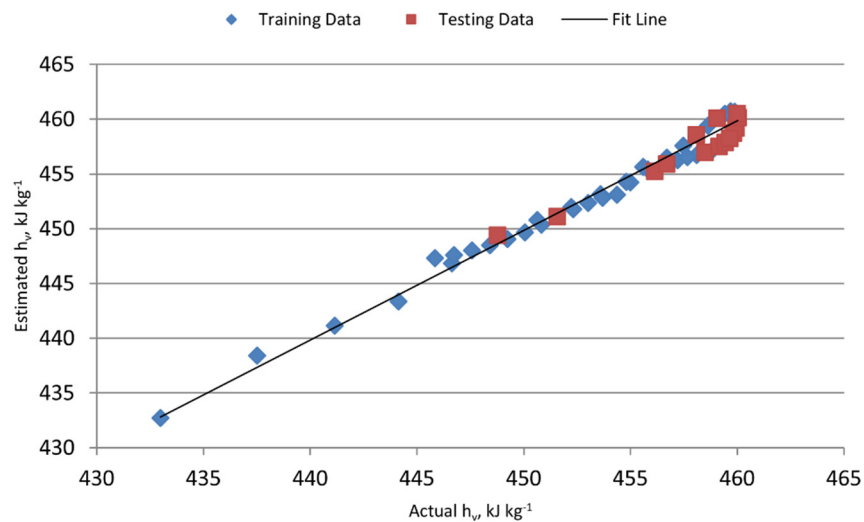




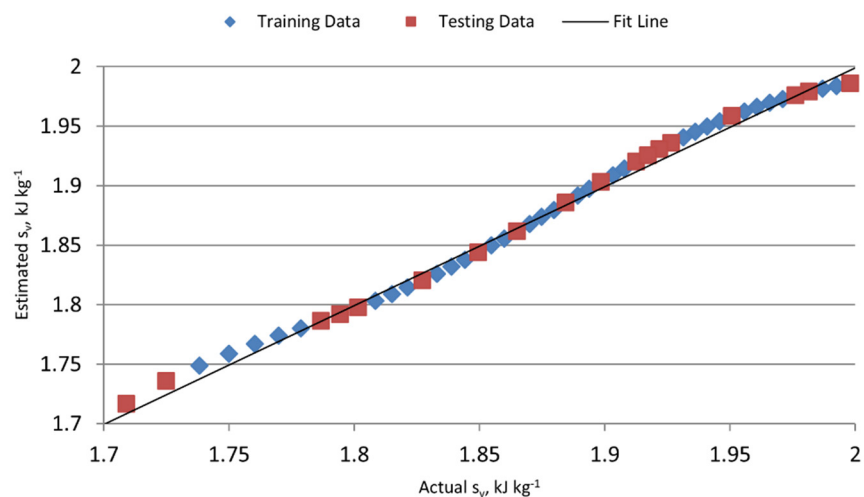


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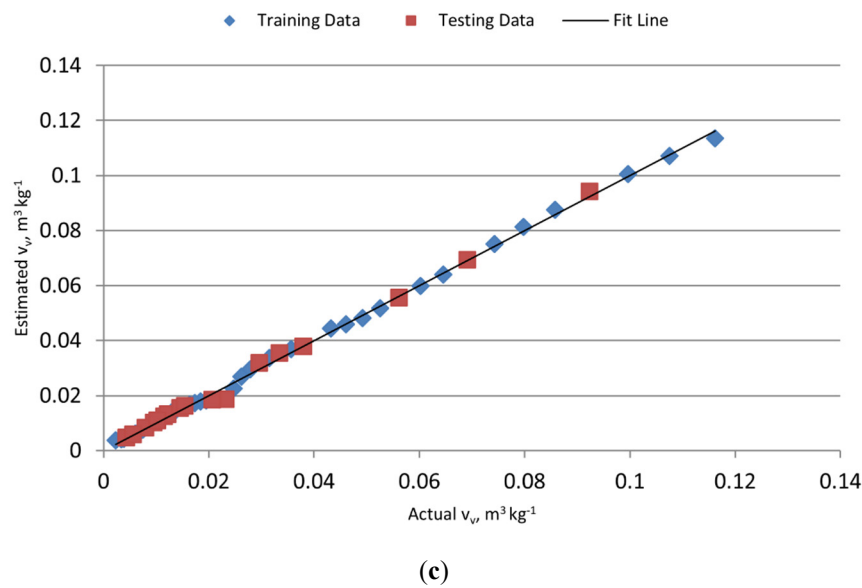
**Figure 4.** Estimated and actual thermodynamic properties plots of refrigerant R452B in the saturated liquid region. (a) Estimated and actual liquid enthalpy plot of refrigerant R452B in the saturated liquid region; (b) Estimated and actual liquid entropy plot of refrigerant R452B in the saturated liquid region; (c) Estimated and actual liquid specific volume plot of refrigerant R452B in the saturated liquid region.



(a)



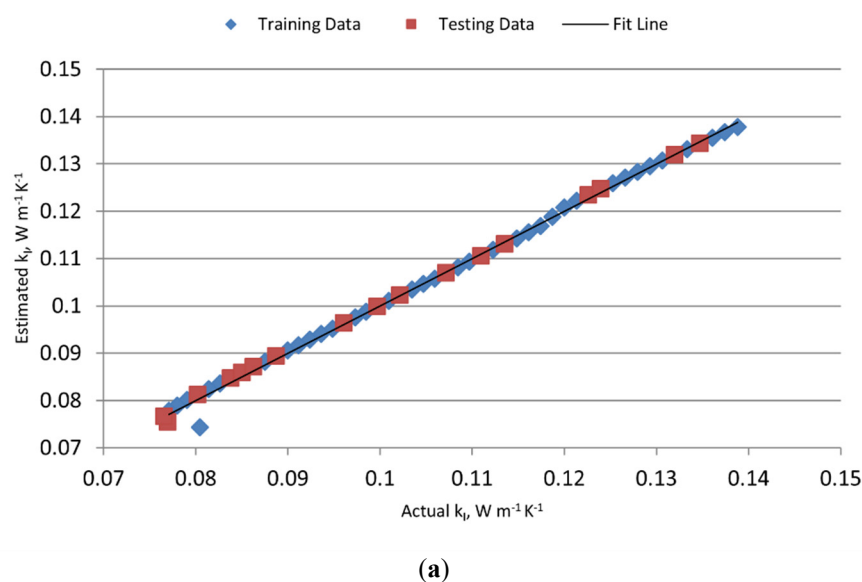
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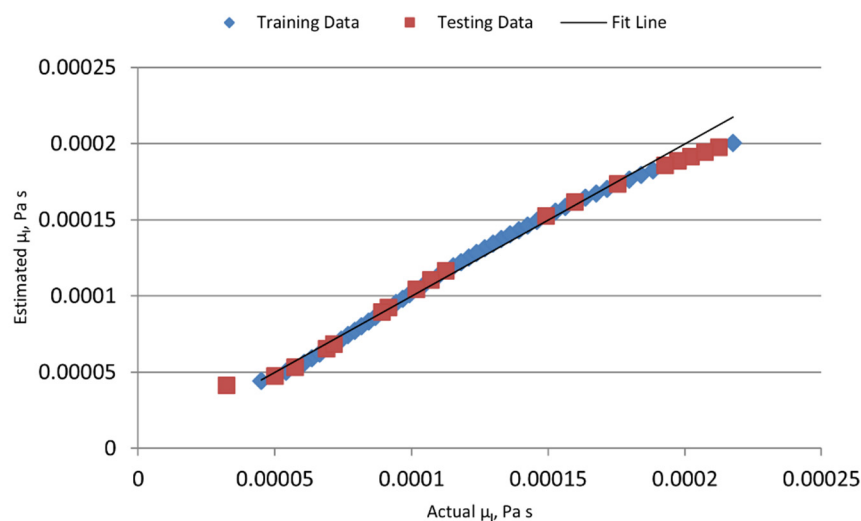


**Figure 5.** Estimated and actual vapor thermodynamic properties plots of refrigerant R452B in the saturated vapor region. (a) Estimated and actual vapor enthalpy plot of refrigerant R452B in the saturated vapor region; (b) Estimated and actual vapor entropy plot of refrigerant R452B in the saturated vapor region; (c) Estimated and actual vapor specific volume plot of refrigerant R452B in the saturated vapor region.

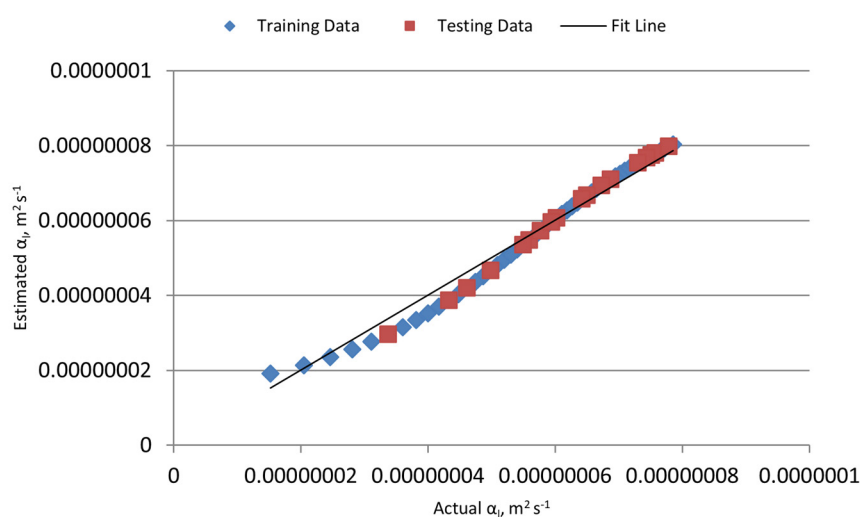
Figures 6 and 7 show how the actual and predicted transport properties, namely thermal conductivity, viscosity, and thermal diffusivity, varied for the different temperature values. The transport properties values were predicted with about 99% accuracy except for thermal diffusivity values. The thermal diffusivity values were predicted with a range of 97% and 99% accuracy.

These results show that the developed model is very successful in predicting the thermodynamic and transport properties of R452B refrigerant.



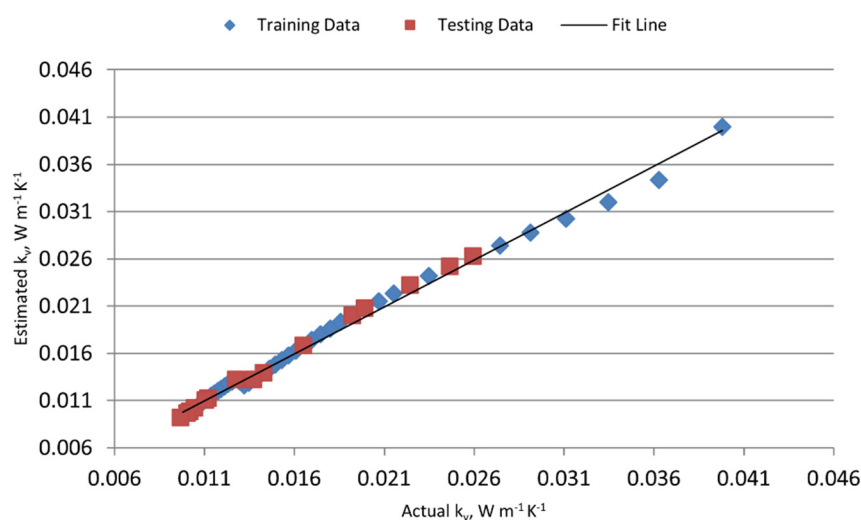


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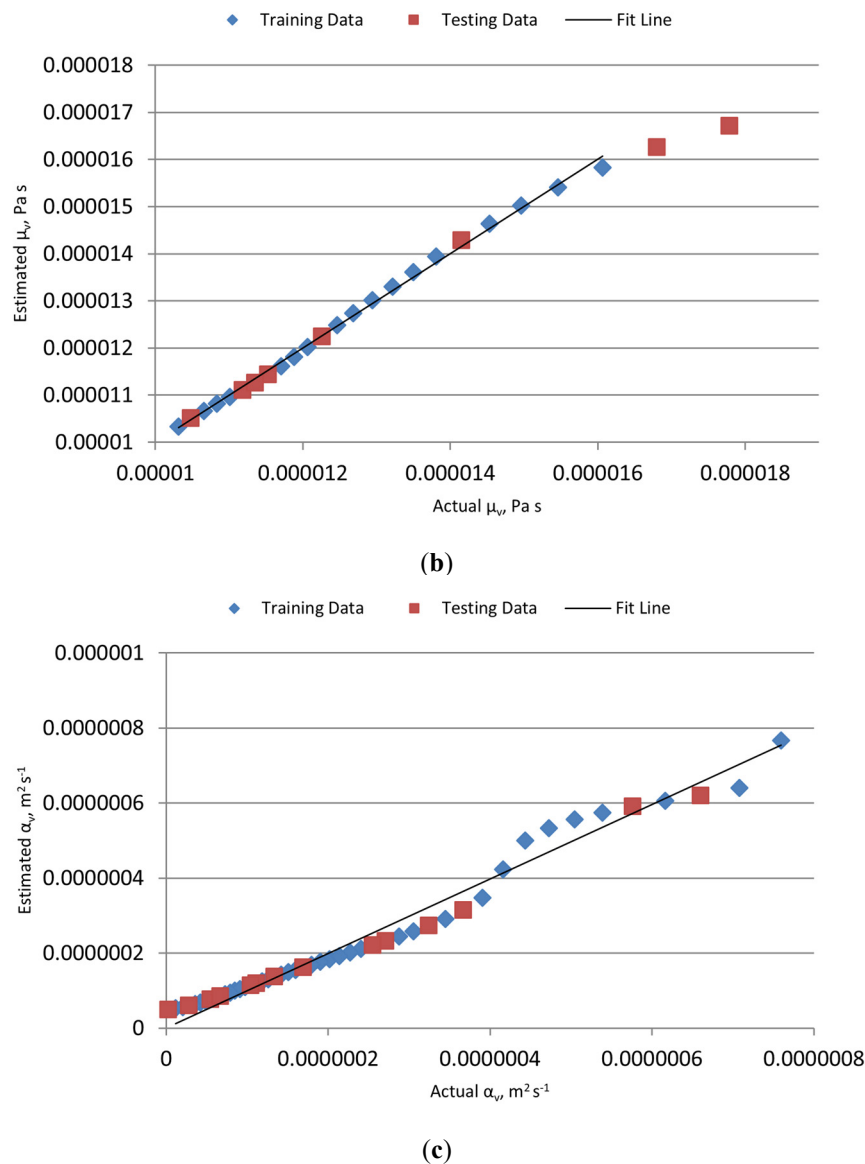


(c)

**Figure 6.** Estimated and actual transport properties plots of refrigerant R452B in saturated liquid region; (a) Estimated and actual thermal conductivity plot of refrigerant R452B in saturated liquid region; (b) Estimated and actual viscosity plot of refrigerant R452B in saturated liquid region; (c) Estimated and actual thermal diffusivity plot of refrigerant R452B in saturated liquid region.



(a)



**Figure 7.** Estimated and actual vapor transport properties plots of refrigerant R452B in vapor region. (a) Estimated and actual vapor thermal conductivity plot of refrigerant R452B in saturated vapor region; (b) Estimated and actual vapor viscosity plot of refrigerant R452B in saturated vapor region; (c) Estimated and actual vapor thermal diffusivity plot of refrigerant R452B in saturated vapor region.

The model's accuracy was assessed using the coefficient of determination ( $R^2$ ) and root mean square error (RMSE). The results, summarized in Table 3, indicate high predictive accuracy across all properties. Table 3 shows the accuracy of the thermodynamic and transport values comparatively. The model is highly reliable, with most  $R^2$  values at 0.99, indicating strong predictive capability. The accuracy values of the predicted values of the thermodynamic and transport properties for the R452B refrigerant predicted using the GEP model clearly demonstrated that these equations are sensitive enough to be used.

**Table 3.**  $R^2$  and RMSE values for predicting thermodynamic and transport properties for R452B refrigerant.

Property	$R^2$ (Liquid)	$R^2$ (Vapor)	RMSE (Liquid)	RMSE (Vapor)
Enthalpy (h)	0.99	0.98	4.88	1.01
Entropy (s)	0.99	0.99	0.014	0.008
Specific volume (v)	0.97	0.99	0.462	1.192
Thermal conductivity (k)	0.99	0.99	11.70	6.09
Viscosity ( $\mu$ )	0.99	0.99	4.40	0.088
Thermal diffusivity ( $\alpha$ )	0.97	0.99	0.036	0.333

Some comparative data values of the target, GEP model, and error values in the saturated region for the R452B are presented in Table 4. The obtained actual value from the Genetron software data is compared to the values predicted using the GEP model, and the deviation values are given in the table presented in this study. The three

sample temperature values in the liquid and vapor regions of the R452B refrigerant were selected randomly. Table 4 can be summarized as follows:

- Enthalpy ( $h$ ,  $\text{kJ kg}^{-1}$ )

In the liquid phase: Model values are generally close to target values, but there is a significant deviation at  $72\text{ }^{\circ}\text{C}$  with a 3.77% error. At other temperatures, the error is below 1%.

In the vapor phase: Model predictions are very close to target values, with the highest error being only 0.18%.

- Entropy ( $s$ ,  $\text{kJ kg}^{-1}\text{ K}^{-1}$ )

In the liquid phase: The highest error is 1.88% at  $-28\text{ }^{\circ}\text{C}$ , while other values remain below 1%.

In the vapor phase: Model values are quite close to target values, with the highest error being 1.19% at  $-30\text{ }^{\circ}\text{C}$ .

- Specific volume ( $v$ ,  $\text{m}^3\text{ kg}^{-1}$ )

In the liquid phase: High error rates are observed, especially at  $-30\text{ }^{\circ}\text{C}$  (5.95%) and  $70\text{ }^{\circ}\text{C}$  (5.41%).

In the vapor phase: The error is lower but still around 3% in some cases.

- Thermal conductivity ( $k$ ,  $\text{W m}^{-1}\text{ K}^{-1}$ )

In the liquid phase: Model values are very close to target values, with the highest error at only 1.15%.

In the vapor phase: The error is generally very low, with the highest being 2.52%.

- Viscosity ( $\mu$ , Pas)

In the liquid phase: The highest error is 1.90% at  $32\text{ }^{\circ}\text{C}$ , while other errors are around 1%.

In the vapor phase: The highest error is 0.90%, indicating overall low error rates.

- Thermal diffusivity ( $\alpha$ ,  $\text{m}^2\text{ s}^{-1}$ )

In the liquid phase: Errors are generally around 2%, with some higher deviations at  $-28\text{ }^{\circ}\text{C}$  (2.31%) and  $32\text{ }^{\circ}\text{C}$  (2.73%).

In the vapor phase: The highest error is 6.84% at  $26\text{ }^{\circ}\text{C}$ , while other errors are around 2%.

**Table 4.** Some comparative values for the accuracy of the predicted model of R452B refrigerant.

Parameters	Liquid				Vapor			
	T ( $^{\circ}\text{C}$ )	Target	Model (Estimated Values)	Percentage Error (%)	T ( $^{\circ}\text{C}$ )	Target	Model (Estimated Values)	Percentage Error (%)
$h$ , $\text{kJ kg}^{-1}$	-14	177.976	177.6825	0.16	-10	451.580	451.071	0.11
	52	294.195	296.9395	0.93	6	456.692	455.874	0.18
	72	349.204	336.0523	3.77	60	448.789	449.364	0.13
$s$ , $\text{kJ kg}^{-1}\text{ K}^{-1}$	-28	0.834	0.849662	1.88	-30	2.015	1.991	1.19
	38	1.220	1.223377	0.28	0	1.936	1.945	0.46
	40	1.232	1.236946	0.40	72	1.689	1.688	0.06
$v$ , $\text{m}^3\text{ kg}^{-1}$	-30	0.00084	0.00089	5.95	-30	0.116	0.113	2.59
	30	0.00103	0.00099	3.88	14	0.026	0.0268	3.08
	70	0.00148	0.00156	5.41	62	0.006	0.0061	1.67
$k$ , $\text{W m}^{-1}\text{ K}^{-1}$	20	0.10594	0.10577	0.16	-12	0.0108	0.01081	0.09
	-26	0.13606	0.13547	0.43	0	0.0119	0.0122	2.52
	58	0.08260	0.08355	1.15	68	0.0398	0.0399	0.25
$\mu$ , Pa s	32	0.000105	0.000107	1.90	14	$12.26 \times 10^{-6}$	$12.24 \times 10^{-6}$	0.17
	48	$8.42 \times 10^{-5}$	$8.32 \times 10^{-5}$	1.19	-10	$11.18 \times 10^{-6}$	$11.10 \times 10^{-6}$	0.68
	-10	0.000171	0.00017	0.58	42	$14.15 \times 10^{-6}$	$14.27 \times 10^{-6}$	0.90
$\alpha$ , $\text{m}^2\text{ s}^{-1}$	20	$6.02 \times 10^{-8}$	$6.06 \times 10^{-8}$	0.66	-12	$6.16 \times 10^{-7}$	$6.05 \times 10^{-7}$	1.79
	32	$5.5 \times 10^{-8}$	$5.35 \times 10^{-8}$	2.73	0	$4.16 \times 10^{-7}$	$4.23 \times 10^{-7}$	1.68
	-28	$7.79 \times 10^{-8}$	$7.97 \times 10^{-8}$	2.31	26	$1.9 \times 10^{-7}$	$1.77 \times 10^{-7}$	6.84

#### 4. Conclusions

This investigation centered on the development of accurate and reliable models for the thermodynamic and transport properties of R452B refrigerant, employing the Genetic Programming (GEP) methodology. The primary aim was to generate comprehensive and wide-ranging data that can serve as a valuable resource for other researchers and engineers in the field. A key focus of this research was to address the challenge of obtaining readily available and accurate data for refrigerant properties, which are crucial for the design, analysis, and optimization of refrigeration systems.

In this study, the temperature of the R452B refrigerant was designated as the primary input parameter. The models were constructed to predict the following crucial thermodynamic and transport properties as output parameters: enthalpy, entropy, specific volume, thermal conductivity, viscosity, and thermal diffusivity. These properties were modelled for both saturated liquid and saturated vapor conditions, providing a complete characterization of the

refrigerant's behavior across its phase change. A significant challenge in refrigeration engineering is the difficulty associated with obtaining experimentally measured values for the thermodynamic and transport properties of refrigerants. This research addresses this challenge by providing a method for obtaining these property values quickly and easily. The models developed in this study enable the accurate and reliable estimation of the thermodynamic and transport properties of R452B refrigerant through the use of the suggested mathematical equations. These equations offer a computationally efficient and dependable alternative to traditional experimental methods or complex simulations. The mathematical equations derived in this study are designed to be easily accessible and applicable, making them a valuable tool for future research and engineering applications. This study successfully developed accurate mathematical models for predicting the thermodynamic and transport properties of R452B refrigerant utilizing the GEP methodology. The proposed models offer a computationally efficient alternative to traditional, often time-consuming and resource-intensive, experimental and software-based methods. These models provide a practical tool for predicting refrigerant behavior without requiring extensive laboratory work or complex computational simulations. The models generated in this study can be readily applied in a variety of engineering design and optimization tasks related to refrigeration systems. This facilitates more efficient system design, performance prediction, and optimization, ultimately leading to improved energy efficiency and reduced environmental impact.

Future research directions should focus on exploring the broader applicability of GEP in modelling the properties of other refrigerants, including those with even lower GWP, and on utilizing these models to optimize the performance of complete refrigeration cycles. This will contribute to the ongoing development of more sustainable and energy-efficient refrigeration technologies.

### Author Contributions

T.K. contributed to conceptualization, methodology, simulation, data curation, writing—original draft, and visualization. A.Ş.Ş. was involved in data curation, writing—review and editing, and supervision.

### Ethics Statement

All procedures performed in studies involving human participants were in accordance with the ethical standards.

### Informed Consent Statement

Consent was obtained from all individual participants included in the study.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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### Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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