

Metaheuristic Evaluation Of Paraffin Wax-Related Flow Assurance Challenges For Optimal Productivity In Onshore Facilities

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Abstract

In this research, paraffin wax deposition models were evaluated using multi-objective genetic algorithm (MOGA). This is a metaheuristic approach to multi-parametric solution of complex mathematical problems. Paraffin wax deposition in onshore production facilities in Nigeria has been noted as a serious flow assurance problem. The aim of the study is to apply a suitable metaheuristic technique to analyse the parameters of paraffin wax-related flow assurance issues in onshore oil and gas facilities in Nigeria, thereby ensuring optimal productivity and operational efficiency. Thus, paraffin wax sample collected from a typical onshore production facility was analysed in a laboratory to determine the thermophysical and transport properties, and the compositions and spectral orientation. The thermophysical and transport properties determined are the wax appearance temperature (WAT), melting point, flash point, liquid density, liquid kinematic and dynamic viscosities. Hence, the melting point of the sample is 32°C, WAT is 52°C, flash point is 191°C, the liquid density and dynamic viscosity of the wax sample at 32°C are respectively, 906kg/m³ and 6.812×10⁻⁵ kg/ms, while at 52°C they are 896kg/m³ and 8.732×10⁻⁵ kg/ms. In the compositional analysis, the molecular mass, molecular formula, structural formula and spectral orientations of the different components were presented. Then, the molar volume of the heaviest component was estimated. Thus, the average minimum times taken by wax particle to diffuse a length equal to its diameter by molecular diffusion, Brownian diffusion, shear dispersion, gravity settling and thermal diffusion are respectively 1.0265 × 10¹⁶ seconds, 4.6650 × 10²⁶ seconds, 2.0004 × 10³ seconds, 9.9010 × 10³ seconds and 4.7453 × 10⁹ seconds.

Key Words: *Piping systems; Flow assurance; Paraffin wax deposition; Multi-objective; Genetic algorithms*

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I. Introduction

Increasing the time taken by paraffin wax particles to diffuse by the different deposition mechanism will reduce deposition rate and improve flow assurance in the onshore facilities in Nigeria. One of the most versatile deterrents to productivity in the onshore oil and gas facilities in Nigeria is the challenges of flow assurance. Flow assurance literally means guarantee of flow, which implies all methods adopted to ensure the efficient, successful and economic flow of fluids (oil, gas and water) from the reservoir to the point of sale or utility [1 – 4]. According to Watson et al [2], flow assurance encompasses system deliverability, thermal behaviour, production chemistry, operability characteristics and system performance. System deliverability is concerned with the effect of pressure drop, reduction in pipeline size and pressure boosting on production. It alters thermal behaviour of the facility thereby causing unwanted temperature changes, insulation options and heating requirements. Its effect on production chemistry relates to hydrates, waxes, asphaltenes, scaling, sand, corrosivity and rheology. Also, the facility operability characteristics is concerned with its effects on start-up, shutdown transient behaviour (e.g. slugging), etc.; while the system performance accounts for mechanical integrity, equipment reliability, system availability, etc. Flow assurance challenges cut across all the sectors of the oil and gas industry, provided flow of fluids is concerned. So, flow assurance is aimed at the uninterrupted transportation of fluids in process and pipelines to ensure increased production rate; reduced production cost; and reduced risk to installations, operators and the environment. But formation of scales, deposition of paraffin wax, asphaltenes, gas hydrate, emulsion, foam and impurities constitute the challenges [5]. Hence, [4] noted that wax deposition in the piping systems poses serious flow challenge to productivity in the Nigerian onshore production facilities.

Thus, Sunday et al [6] noted that the most worrisome of the flow assurance challenges are waxes, hydrates, asphaltene and scales that usually form in the flow channels. Paraffin wax deposition is one of the most critical problems to productivity in the onshore facilities in Nigeria [4]. It occurs because of the reduction of pipe

wall temperature below the wax appearance temperature [7]. Paraffin wax is a class of hydrocarbon that is natural constituent of any crude oil and most gas condensates [8, 3, 9]. According to Anisuzzaman et al [10], wax is classified into paraffin wax and microcrystalline wax in that the paraffin wax is a hydrocarbon belonging to the straight chain alkane series of 20 to 40 carbon atoms, while the microcrystalline waxes are the branched and cyclic chain hydrocarbons with 30 to 60 carbon atoms. Paraffin wax is an odourless pale yellowish-white solid at room temperature (saturated hydrocarbon fraction) with a density of about 0.9 g/cm^3 and melting point between 46°C and 68°C [11]. Its deposition is a popular flow assurance challenge in the flow systems of Fischer-Tropsch synthesis in which natural gas is being converted into liquid fuels [12]; and deals with the heat and mass transfer, and other issues associated with flow as they concern the motion of fluids in the oil and gas piping facilities. This implies that once the temperature of waxy fluid in the flow line reduces (by conduction, convection and radiation) below the wax appearance temperature (WAT), wax molecule begins to precipitate and further drop in the temperature leads to eventual deposition of the molecules on the walls of the piping systems [13]. WAT is also known as the solubility temperature limit of wax [14]. The deposition continues to build up to a point where the flow lines may be totally or partially blocked. So optimal productivity in an onshore facility in Nigeria depends on the free flow of hydrocarbon and associated fluids in the pipelines.

Although the concept of flow assurance was initially developed on the background of transportation of hydrocarbon fluids from reservoir to point of sale, particularly in subsea installations [3], the analysis of its challenges and their mitigation strategy in the onshore process and pipeline facilities is sacrosanct. This is because of the prevalence of those challenges in the onshore process facilities in Nigeria. They block flow lines and truncate the performance of instrumentations thereby deterring the free flow of fluids in pipelines and the associated equipment and proper process monitoring. Also, the flow assurance challenges alter temperature and pressure distributions in piping systems. Particularly paraffin wax deposition in pipelines and systems shuts down production, increases operational risk, causes production losses and irreparable damage to equipment [15]. This and similar flow assurance challenges increase facility operations cost, reduce production rate and increase man-hour without corresponding increase in output, hence low productivity. The challenges also cause the breakdown of equipment – pumps, compressors, flow lines and vessels – due to pressure surge, back flow and loss of suction.

So far pigging, retro jetting and chemical cleaning are some of the available mechanical and chemical approaches towards the mitigation and, or management of flow assurance challenges due to paraffin wax deposition; each of these methods leads to partial or, sometimes, total shutdown of the plant thereby interrupting production. Also, it should be noted that each of these methods involves huge capital investment and exposes the installations, operators and the environment to high risk. Their application frequency is relatively high. They are often contracted to third-party experts, the wastes removed constitute high environmental pollutants. Therefore, revenue margin is adversely affected. Bryan [16] noted that too frequent pigging results in serious loss of revenue while infrequent pigging can result in pig being stocked in the pipeline due to heavy mass of wax deposit. Southgate [17] recommends removal of wax deposits by pigging and argued that prevention of wax deposition by pipeline insulation, active heating of the pipes and chemical dosing with wax inhibitors are not economically viable however it should be noted that the application of pigs is affected by pipeline network configuration and bore size. More so pigs cannot run through pump flow channels and constricted tubes. Research shows that despite the thermal, mechanical and chemical methods, there are currently simulation approaches to mitigating flow assurance challenges generally [18, 19] but their practical implementation, particularly in onshore facilities has not been generally ascertained. It is important to identify the flow assurance challenges due to paraffin wax deposition; the factors affecting it and provide solution set to control it. Hence, there is explicit need for a metaheuristic approach to the evaluation, modelling and offer inline prevention of wax deposition for optimal flow assurance in onshore facilities in Nigeria, to achieve optimal productivity. Therefore, the aim of the study is to apply a suitable metaheuristic technique to analyse the parameters of paraffin wax-related flow assurance issues in onshore oil and gas facilities in Nigeria, ensuring optimal productivity and operational efficiency by defining the operational settings to minimize paraffin wax deposition rate. This increases the time taken by paraffin wax particle diffuse and deposit on the inner walls of the piping system.

II. Related Literature

Thermophysical and Transport Factors of Paraffin Wax Deposition

The rate at which paraffin wax deposits in the onshore oil and gas pipeline is dependent on its deposition process, which in turn is affected by several factors. Theyab [7] noted that the temperature of pipe wall, temperature of oil, ambient temperature, oil composition, ambient temperature, are some of the most critical temperature-related factors affecting wax deposition process. Bautista-Parada *et al* [20] studied the influence of pipe wall temperature on the thickness of paraffin wax deposit using the wax. Kelechukwu et al [21] studied the influencing factors governing paraffin wax deposition during crude oil production; the result of the study showed that the rate of paraffin wax deposition decreases with increase in temperature differential. The two conditions involved in wax deposition in oil pipelines with regards to variables are that crude oil layer closest to the pipe

wall should have lower temperature than the wax appearance temperature, and that the temperature of the pipe wall must be less than temperature of the oil [22].

Though the temperature-related factors are not the most comprehensive predictive factors according to Huang et al [23], their effects on deposition vary at different conditions. In their review of heat transfer mechanism for wax deposition, Mehrotra et al [24] argued that wax deposition process is controlled by heat transfer and so, it is predominantly thermally driven process. Also, Mehrotra et al [25] maintained that wax deposition in pipeline is a heat transfer process as it is predominantly controlled by thermal resistances due to convection in the flowing oil and conduction across the deposit layer. The study revealed that oil temperature, pipe wall temperature, oil WAT, heat transfer coefficient, average thermal conductivity, overall thermal difference, thermal conductivity of pipe material, insulation and thermal conductivity of insulation material are among the thermal related factors affecting the thickness of paraffin wax deposit. In their critical review of wax deposition mechanisms, Sousa et al [26] noted that absolute temperature is a function of the time taken by a wax to diffuse a length equal to its diameter by molecular diffusion, Brownian diffusion and thermophoresis. Thus, crystallization of solid paraffin wax particles occurs due to the thermodynamic instability of the liquid in the piping system [27]. Xu [28] conducted a study to reduce the viscosity of heavy oils by emulsification and so reduce paraffin wax deposition rate. Ridzuan et al [29] evaluated the factors influencing the deposition of wax to include rotational speed, cold finger temperature, and experimental duration and wax inhibitor type. Thus, cold finger temperature was found to be the most influencing factor affecting wax deposition.

Many researchers have studied the transport factors affecting wax deposition in pipelines. Though most of these studies are concerned with offshore pipeline facilities, it is important to note that the effects of these factors also cut across the onshore facilities. The transport factors here in flow rate, viscosity, shear stress, shear rate and pressure. Elganidi et al [30] noted that wax deposition increases with an increasing resident time. This is because decrease in flow rate increases residence time of waxy fluid in the pipeline. They also reviewed that increase in shear stress decreases the thickness of wax deposit in the pipeline. Bautista-Parada *et al* [20] studied the influence of flow rate, deposition time and pipe wall temperature on the thickness of paraffin wax deposit using the wax deposition model and concluded that increased flow rate reduces the maximum deposit thickness. Kelechukwu et al [21] studied the influencing factors governing paraffin wax deposition during crude oil production; the result of the study showed that while the rate of paraffin wax deposition decreases with increase in temperature differential and flow rate, it increases with increase in residence time. Haj-Shafiei [31] studied the effects of flow rate and shear rate on wax deposition in pipeline thereby noting that irrespective of the prevalent flow condition (laminar or turbulent), increasing the flow rate of waxy mixture decreases wax deposition. Also, increase in flow rate increases the rate of sloughing (shearing) of the wax deposit [31]. Hernandez et al [32] noted that paraffin wax deposition under single-phase flow conditions depends on shear stripping, deposit aging, flow regime and fluid properties among other factors.

Paraffin Wax Deposition Models

Paraffin wax deposition is known as a serious flow assurance challenge in the oil gas pipeline facility generally because of its effects on the effectiveness of heat and mass transfer processes, including production losses [32, 14]. Thus, different models have been developed over time to predict it. In their critical review of the modelling of wax deposition mechanisms, Azevedo and Teixeira [33] opined that molecular diffusion is the most dominant paraffin wax deposition mechanism and noted that other mechanisms like Brownian diffusion also contribute to the deposition. Mahir et al [34] proposed a transport model bothering on heat and mass transfer frameworks for paraffin wax deposition in pipeline. Mahir [35] also emphasized the importance mathematical models for paraffin wax deposition based on thermodynamic and transport phenomena, and the model computes the mass or volume of wax deposited as a function of time. According to Daraboina and Alhosani [36], wax deposition models can aid in the estimation of optimal conditions to reduce or manage wax deposition in transport flowlines. Hence, the wax deposition models show the relationship between the deposition rate and the affecting parameters.

Basically, these relationships characterize the wax deposition mechanisms that have been studied under different phenomena including molecular diffusion, Brownian diffusion, shear dispersion, shear sloughing, gravity settling and thermal diffusion [26]. They are the processes through which paraffin wax is deposited on the inner walls of the piping systems [37]. Ragunathan et al [38] reviewed the six wax deposition mechanisms and noted that molecular diffusion is the dominant. Lonje and Liu [39] noted that molecular diffusion is the most important wax deposition mechanism while gravity settling is not given much attention under flow condition due to its low impact on wax deposition in the scenario. Makwashi [40] revealed that some of the wax deposition mechanisms, particularly, molecular diffusion, shear stripping and shear dispersion are being incorporated into wax deposition models to simulate wax deposition. Obaseki and Paul [41] applied wax deposition model that is based on the molecular diffusion by Fick's law to predict wax deposition thickness. Sousa et al [26] noted that the knowledge of the background of wax deposition mechanisms is the key factor to prevent wax precipitation

and deposition control. Thus, they showed that the relative importance of every mechanism is estimated by the determination of the time (in seconds) taken by a wax particle to diffuse a length equal to its diameter.

Metaheuristic Evaluation of Wax Deposition Models

Due to the inherent nature of paraffin wax deposition in piping systems and its effect on flow assurance, there is need for novel approaches to its prediction and mitigation. Researchers have developed AI-driven models that combine machine learning with metaheuristics to forecast paraffin wax deposition in piping systems [42]. Kamari et al [43] proposed a novel approach to develop a predictive model for estimation of wax deposition. This model is metaheuristic and provided superior accuracy and generality when compared with other approaches. Chu et al [44] optimized an adaptive neuro fuzzy interference system (ANFIS) model by particle swarm optimization (PSO), which is a metaheuristic, to reliably predict wax deposition in pipeline. Ahmadi [45] coupled fuzzy logic and genetic algorithm (GA) to propose robust and efficient method for predicting the amount of wax deposition. This is a data-driven approach for predicting wax deposition in piping systems. Hence, metaheuristic approaches have shown promising results in evaluation of wax deposition rates [46].

Thus, metaheuristic algorithms are viable tools for complicated modelling and optimization problems [47]. It should be noted that metaheuristics is stochastic in nature and allows for the solution of problems in many areas [48]. Genetic algorithm is one of the most popular metaheuristic algorithms and it is population-based [49]. Asghari and Navimipour [50] noted that genetic algorithm is one of the most widely known metaheuristic algorithms. It shows very good performance compared with other metaheuristics [51]. Hence, genetic algorithm is one of the metaheuristic algorithms to solve complex mathematical problems. When the problems involve finding two or more solution sets simultaneously, the multi-objective genetic algorithm is evoked [52]. Therefore, since wax deposition involves several mechanisms (including molecular, Brownian, shear stripping, gravity settling and thermal diffusion) at a time; application of the multi-objective genetic algorithm is a novel approach to optimally setting the deposition parameters.

III. Materials And Method

Sample Collection and Experimental Procedure

The paraffin wax sample was collected from the fallouts at the wax treatment unit of Escravos gas-to-liquid (EGTL) plant. EGTL plant is an onshore oil and gas facility that converts natural gas into liquid fuel through Fischer Tropsch synthesis [53]. The facility is in southern Warri, Nigeria, and the process is characterized by high production of petroleum wax. Hence, there is recurrent flow assurance problem due to paraffin wax deposition in the piping systems. The paraffin samples are shown in plate (1):



Plate 1 Paraffin wax sample

The experimental apparatus used included electronic weighing balance, beaker, measuring cylinder, crucible, thermometer, Redwood viscometer, electric burner, heating element cloud point and pour point chamber and flash point tester.

The paraffin wax sample was experimentally analysed at the Petro-Chemical Engineering Laboratory of Rivers State University of Science and Technology, Nkpolu, Port Harcourt, Rivers State. The ambient temperature of the laboratory was measured and recorded, and the weighing balance was calibrated with an error of $\pm 0.47\text{g}$ recorded. Mass of the measuring cylinder was measured and recorded, and mass of the beaker was measured and recorded. 5.00g of the solid wax sample was heated in test tube containing thermometer, the rise in temperature was being monitored until the entire solid turned to liquid [54, 55]. The temperature at which the solid completely turned to a liquid was noted and recorded. Then an arbitrary mass of solid wax was heated up to

the melting point and 20 ml (i.e. $2.0 \times 10^{-5} \text{ m}^3$) was collected and weighed at the melting point. Thereafter, heating continued, and the mass of the liquid was measured at every 20°C rise in temperature, the results were recorded. Also, a certain quantity of the molten paraffin wax was taken to pour point and cloud point chamber in a test tube together with the thermometer. The temperature of the liquid was continuously monitored as the liquid cooled and changed from the liquid phase to solid phase. The temperature at which the first whitish cloud appeared and the temperature at which the liquid cannot flow were noted and recorded.

Furthermore, a portion of the solid paraffin wax was heated in a test tube and the temperature change monitored continuously with a thermometer. The temperature at which the entire solid turned to liquid was noted and recorded. Also 40ml of the paraffin wax liquid at 60°C was introduced into the chamber of a Redwood viscometer, with the stopping ball fitted and the bath filled with water at a constant temperature of 100°C . The stopping ball was lifted and the stopwatch started simultaneously. The time (in seconds) for the 40ml of paraffin wax to be fully collected through the orifice of the Redwood viscometer chamber was noted and recorded. This process was repeated four more times at 70°C , 80°C , 90°C and 100°C , and the respective times of flow were similarly recorded.

Data Presentation and Analysis

Then the kinematic viscosity of the paraffin wax was calculated using the following equation [56, 57].

$$\nu = At - \frac{B}{t} \quad (1)$$

where ν is the kinematic viscosity of the sample (in centi-stokes, cSt), A (which is taken as 0.0026 flow times up to 100 seconds and 0.00247 for flow times above 100 seconds) is the viscometer constant which can be determined by equipment, B (which is taken as 1.72 for flow times up to 100 seconds and 0.5 for flow times above 100 seconds) is the coefficient of kinetic energy, and t is time of flow (in seconds).

The density of the sample is the ratio of average mass of the sample in liquid state to the volume of the liquid sample. It was determined using equation (2).

$$\rho_s = \frac{m_s}{V_s} \quad (2)$$

Where m_s is the average mass of sample in liquid state and V_s is volume of sample in liquid state. Dynamic viscosity of the sample was computed using equation (3).

$$\mu = \nu \rho_s \quad (3)$$

Given that the molecular mass of the sample is M , then the molar volume of the sample was determined using equation (4).

$$V_m = \frac{M}{\rho_s} \quad (4)$$

Hence, the density, viscosities and flow rate of different samples of varying masses at different temperatures were shown in table (1). The table shows the effects of change in temperature on the mass, density, kinematic viscosity, dynamic viscosity and volume flow rate of the paraffin wax samples.

Table 1 Effects temperature change on mass of liquid paraffin wax

S/N	T_s ($^\circ\text{C}$)	m_s (kg)	ρ_s (kg/m^3)	$\nu \times 10^{-8}$ (m^2/s)	$\mu \times 10^{-5}$ (kg/ms)	$q \times 10^{-4}$ (m^3/s)
1	60	0.01784	892	6.86	6.12	9.50
2	70	0.01774	887	5.44	4.83	10.46
3	80	0.01773	881	5.10	4.49	10.71
4	90	0.01749	874	4.39	3.84	11.26
5	100	0.01747	869	3.21	2.80	12.26

Model Evaluation Methods

Sousa et al (2020) studied the impact of each of the wax deposition mechanisms and noted that the time taken by a wax particle to diffuse a length equal to its diameter by molecular diffusion, Brownian motion, shear dispersion, gravity settling and thermophoresis are respectively given as.

$$t_m = \frac{d^2}{D_m} = \frac{1.70125 \times 10^{16} d^2 \mu V_{solute}^{0.6}}{(M_w)^{1/2} T} \quad (5)$$

$$t_B = \frac{d^2}{D_B} = \frac{3\pi\mu d^3}{K_B T} = \frac{6.82634 \times 10^{23} \pi \mu d^3}{T} \quad (6)$$

$$t_s = \frac{d^2}{D_s} = \frac{40}{\omega \phi} \quad (7)$$

$$t_g = \frac{d}{V_g} = \frac{1.8367\mu}{d(\rho_p - \rho)} \quad (8)$$

$$t_T = \frac{d}{V_T} = \frac{3.8461d\rho T(2k + k_p)}{k\mu\nabla T} \quad (9)$$

where t_m , t_B , t_s , t_g and t_T are respectively times (in seconds) taken by paraffin wax to diffuse a particle equal to its diameter by molecular diffusion, Brownian diffusion, shear dispersion, gravity settling and thermal diffusion (thermophoresis), d (in m), μ (in Pas) is the fluid viscosity, V_{solute} (in m^3mol^{-1}) is the molar volume of the solute at normal boiling point, M_w (in kg/mol) is the molecular weight, T (in K) is the temperature, K_B is the Boltzmann constant ($1.3806485 \times 10^{-23}m^2kg s^{-2}K^{-1}$), ω (in s^{-1}) is the mean shear rate of of suspending fluid, ϕ (in m^3/m^3) is the volumetric concentration of wax suspended particles ($0 < \phi < 0.20$), ρ_p (in kgm^{-3}) is density of particle, ρ (in kgm^{-3}) is density of the fluid, k (in W/mK), k_p (in W/mK) and ∇T the thermal gradient. Then, D_m (in m^2s^{-1}) is the molecular diffusion coefficient, D_B (in m^2s^{-1}) is Brownian diffusion coefficient, D_s (in m^2s^{-1}) is shear dispersion coefficient, V_g (ms^{-1}) is settling velocity and V_T (in ms^{-1}). This implies that the diffusion time depends on molecular diffusion, Brownian diffusion and thermal diffusion depends on the absolute temperature of the fluid. Also, paraffin wax deposition in the piping system is a multiparametric process.

Thus, the optimal settings of these parameters were defined using the multi-objective genetic algorithm toolbox available in MATLAB. It involves creation of initial population, evaluation fitness for each population, storage of best individual, creation of mating pool, finding the crossover generation, defining the optimal solution. If the optimal solution satisfies the set objectives, the optimization is terminated; otherwise, the population is reproduced with few of them ignored and mutation performed. This was performed with MATLAB optimization toolbox that offers double vector, bit string population type of size 200 since the number of variables is more than 5.

IV. Results And Discussion

Thermophysical Characteristics

The lab results showed that the flash point of the sample is $191^\circ C$ and the melting point is $52^\circ C$, while the pour point is $32^\circ C$. The density and dynamic viscosity of the wax sample at $32^\circ C$ are $906kg/m^3$ and $6.812 \times 10^{-5} kg/ms$, while at $52^\circ C$ they are $896kg/m^3$ and $8.732 \times 10^{-5} kg/ms$. Thus, the variation of density, kinematic viscosity, dynamic viscosity and volume flow rate with temperature are shown in figures (1). Figures (1a), (1b) and (1c) show that density, kinematic viscosity and dynamic viscosity of the paraffin wax sample decrease as temperature increases, while figure (1d) shows that the volume flow rate increases as temperature increases.

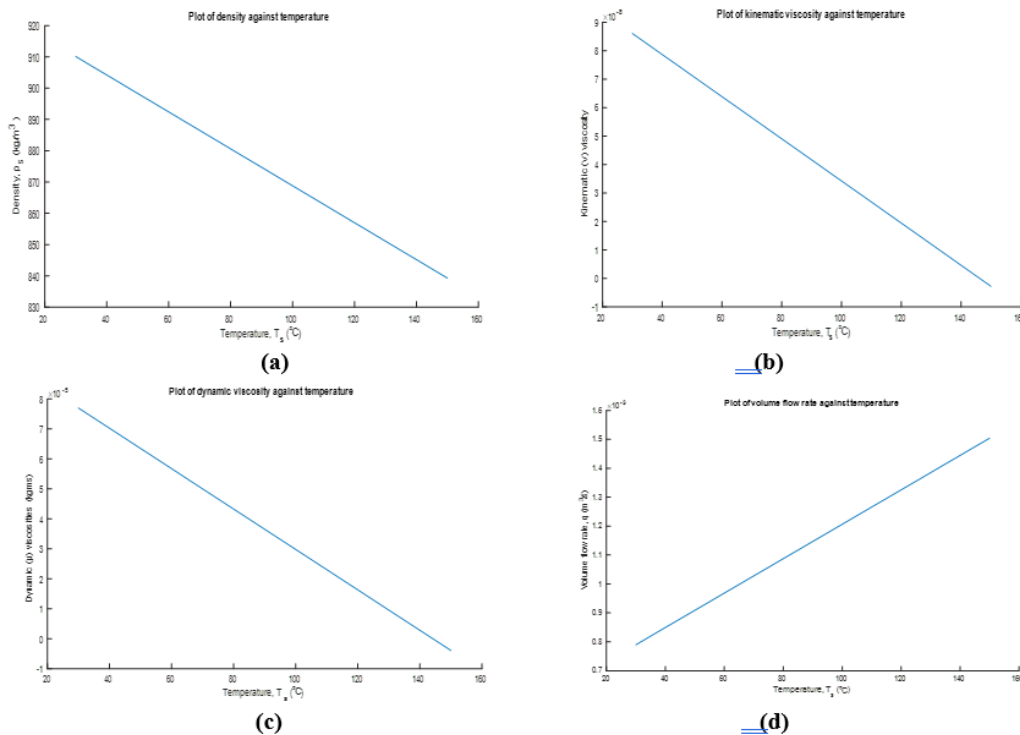


Fig. 1 Plot of (a) density, (b) kinematic viscosity, (c) dynamic viscosity, and (d) volume flow rate against temperature of paraffin wax

Thus, maintaining the temperature of the wax fluid between 52°C and 191°C, both exclusive, assures continuous flow without deposition on the internal wall of the piping system without fire outbreak.

XRD Characteristics

The result of the x-ray diffraction (XRD) analysis performed was shown in figure (2). The figure is a plot of abundance against time. It indicates the crystalline and amorphous characteristics of the sample. Hence, there are 20 peak points with the peak values indicated.

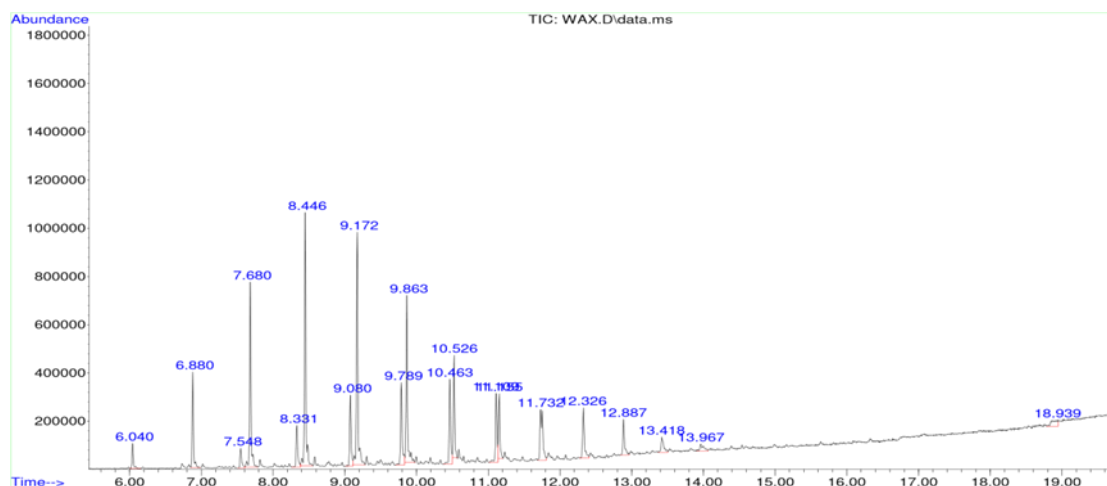


Fig. 2 XRD spectrum of paraffin wax sample

The sharp peak points indicate the regions of crystallinity, while the broad peak points indicate amorphous regions. Peak number 6 has the highest abundance with 1432183 corrected area. It implies that the sample exhibited both crystalline and amorphous characteristics. Hence, the crystalline regions are composed of the linear alkane series, while the amorphous sides are composed of the branched-chain alkanes.

Multi-Objective Genetic Algorithms

The metaheuristic evaluation of the time taken by a particle to diffuse a length equal to its diameter by molecular diffusion (t_m), Brownian diffusion (t_B), shear dispersion (t_s), gravity settling (t_g) and thermal diffusion (t_T) considering the measured thermophysical parameters is presented in the score diversity in figure (3). This shows the result of multi-objective optimization using genetic algorithms, with values of the objectives in-boxed. The histogram is a plot of the score diversity. The score diversity is a graphical presentation of the distribution of the range of solutions of each objective function for the population of individuals. It measures the difference that lies within the solution sets (individuals) and indicates that for 100 individuals, the best solution ranges as shown for t_m , t_B , t_s , t_g and t_T respectively.

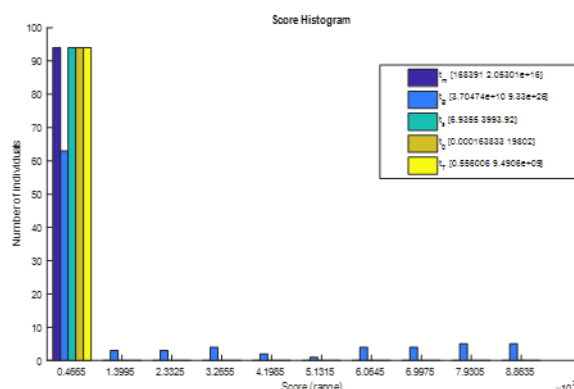


Fig. 3: Plot of Score Diversity in Multi-Objective Genetic Algorithms

The solution sets for each of the deposition times displayed represent the Pareto front as a set of non-dominated solutions. These are optimal values of the objective functions. It implies that the result displayed are the range of best minimum values of the time taken by a particle to diffuse a length equal to its diameter by

molecular diffusion, Brownian diffusion, shear dispersion, gravity settling and thermophoresis. The heights of the bins represent the distribution of the scores to various individuals. Thus, the diversity in the scores presents better trade-off in the solution sets. Also, the diversity helps in the attainment of global optimal solution thereby preventing the iteration from terminating at the heuristic level. Hence, the solution is metaheuristic. Therefore, the average minimum times taken by wax particle to diffuse a length equal to its diameter by molecular diffusion, Brownian diffusion, shear dispersion, gravity settling and thermal diffusion (thermophoresis) are respectively 1.0265×10^{16} seconds, 4.6650×10^{26} seconds, 2.0004×10^3 seconds, 9.9010×10^3 seconds and 4.7453×10^9 seconds.

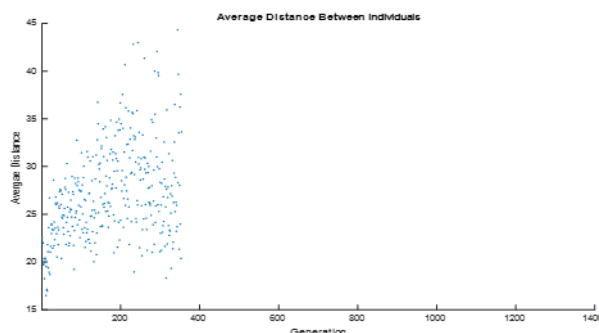


Fig. 4: Plot of Average Pareto Distance between individuals in Multi-Objective Genetic Algorithms

The plot of average Pareto distance is presented in figure (4). This plots the average distance between individuals against the generation of individuals. It shows the average pairwise distance between solutions in the population at each generation, the diversity, convergence and stability of the solution set. The diversity is explained by the spread of the solutions. The convergence is explained by how much the population moves towards the Pareto front. Then the stability is explained by how much the algorithm maintains a healthy balance between the prevailing exploration and exploitation. Hence, a high average Pareto distance indicates a high diversity, while a low average Pareto distance indicates a low diversity. When the diversity is high, the population is widely exploring the search space, and when it is low, the population may be converging towards a solution. High diversity ensures avoidance of premature convergence, while diversity can be good if it occurs near the Pareto front but bad if it occurs too early. Thus, there are more than 400 generations being covered in the plot. The distance between individuals is well distributed. Therefore, the diversity is high.

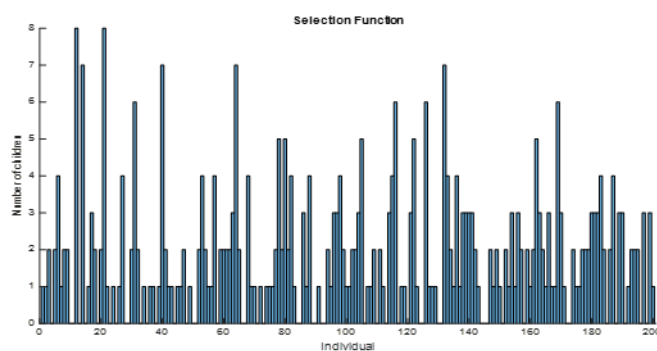


Fig. 5: Plot of Selection Function in Multi-Objective Genetic Algorithms

Plot of the selection function is shown in figure (5). It shows plot of number of children against individuals and provides an understanding of how individuals are chosen from the population to reproduce and move towards better solution set. It determines which individuals are selected for mating considering their prevailing fitness that depends on Pareto dominance, crowding distance and rank. In the case of Pareto dominance, the non-dominated solutions are preferred for mating. The crowding distance is basically considered to maintain diversity, while rank ensures balanced convergence and spread.

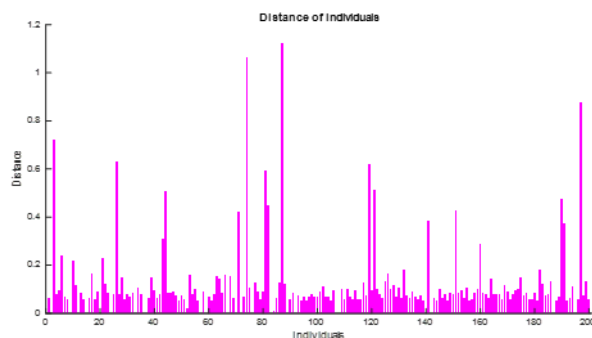


Fig. 6: Plot of Distance Function in Multi-Objective Genetic Algorithms

The distance function plot shown in figure (6) helps to understand how solutions are distributed across the Pareto front and how divergent or convergent the population of the individuals is. It shows the distance between individuals in the population, between each solution set and the nearest neighbour or between solution set and a reference point. Hence, the distance to the Pareto front is small over generations, the population shows good convergence toward the optimal point; if it is large over generations, the algorithm may be struggling to find optimal solution set. Also, if the distances are uniformly spaced, it implies that the diversity is good and the solution sets are well spread across the Pareto front; but if they are clustered or there are gaps in the plot, it implies that the diversity is poor, and some regions of the Pareto front are not duly represented. Thus, in figure (9) the largest distance lies between 85th and 95th individual and the bins of the plot are well distributed across the individuals. This shows good diversity and optimal results.

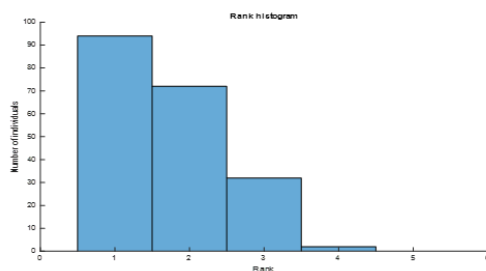


Fig. 7: Plot of Rank Histogram Function in Multi-Objective Genetic Algorithms

The plot of rank histogram is presented in figure (10) helps to understand how well the population is distributed across different Pareto ranks. Like other plot functions, it visualizes the relationship between number of individuals and the different ranks. The bins of the histogram show number of individuals at each Pareto rank, and rank 1 has the highest number of individuals followed by rank 2 and so on. This implies that the non-dominated solution falls in rank 1, and rank 2 is dominated by rank 1, in that order. Since most of the individuals (about 95) are in rank 1, it means that they are non-dominated, and the population converged well. Also, there is strong selection pressure indicating that only the best solutions (individuals) survived the selection.

Plot of average Pareto spread shown in figure (11) shows the change in distance measure of individuals with respect to the previous generation. The average spread ranging from 0 to 1 plotted against the generation shows the distribution in each generation of about 500. This illustrates how many individuals that exist in each generation. Thus, an average spread of 0.0483865 is indicated in the plot. The plot helps one to assess how well the algorithm is maintaining diversity across the Pareto front.

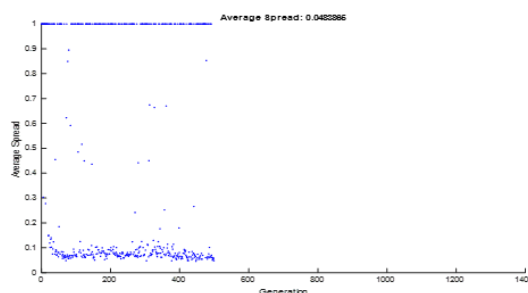


Fig. 8: Plot of Average Pareto Spread Function in Multi-Objective Genetic Algorithms

Pareto fronts of the diffusion times plotted show the set of non-dominated solutions of the objective functions. They plot the function values for all non-inferior solutions with scatters used to represent the solutions along the Pareto front such that each of the points represents different solutions. The plots show the relationship between conflicting objectives and reveal how the algorithm balances them. Hence, an attempt to improve the solution set of any of the objective functions will worsen the solution set of the other objective function.

Figure (9a) shows the Pareto frontier of the time taken by wax particle to diffuse a length equal to its diameter by Brownian diffusion (t_B) against the time taken by wax particle to diffuse a length equal to its diameter by molecular diffusion (t_m). It can be seen that, though the times taken by Brownian diffusion and molecular diffusion increase progressively, particle deposition by molecular diffusion began earlier than deposition by Brownian motion.

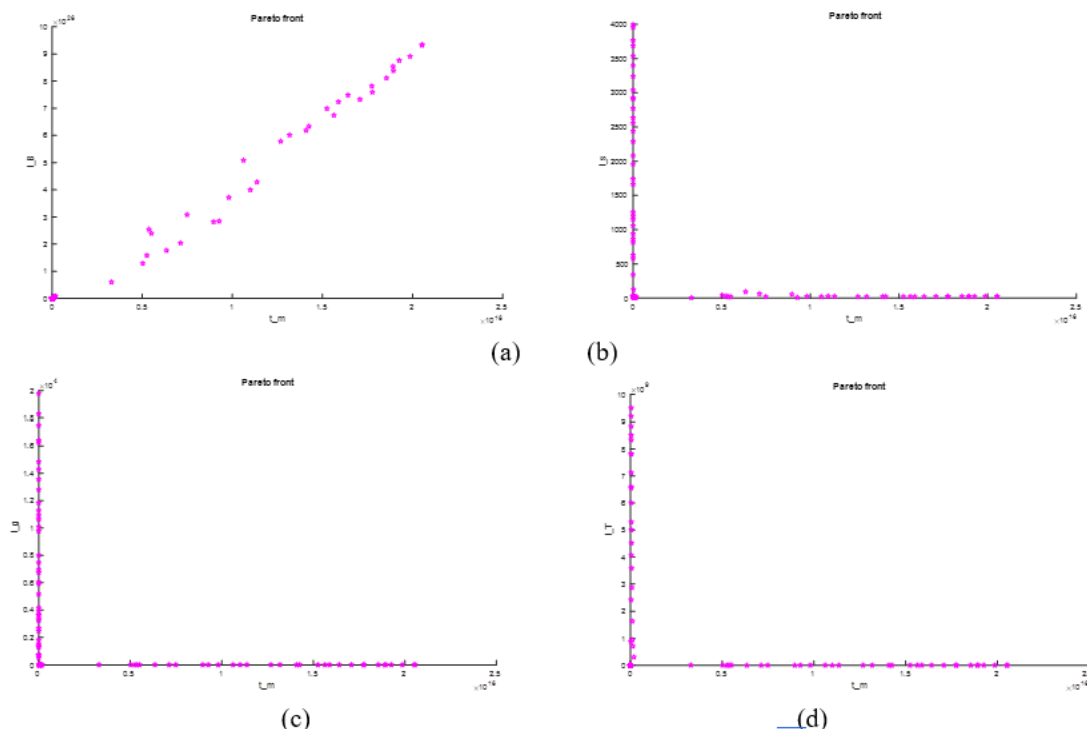


Fig. 9: Plot of Pareto Frontier of (a) t_B , (b) t_s , (c) t_g and (d) t_T against t_m

The plot of Pareto front of the time taken by wax particle to diffuse a length equal to its diameter by shear dispersion (t_s) against the time taken by wax particle to diffuse a length equal to its diameter by molecular diffusion (t_m) is shown in figure (9b). Each of the objective functions attained optimal solution at the expense of each other. The plot indicates that the wax deposition by shear dispersion is independent on wax deposition by molecular diffusion. This is indicated by the plot points appearing on the respective axis of the times.

Figure (9c) shows the Pareto front of the time taken by wax particle to diffuse a length equal to its diameter by gravity settling (t_g) against the time taken by wax particle to diffuse length equal to its diameter by molecular diffusion (t_m). Also, each of the two objective functions attained optimal solution at the expense of each other. The plot also indicated that wax deposition by gravity settling and wax deposition by molecular diffusion are independent on each other.

The Pareto front of the time taken by wax particle to diffuse a length equal to its diameter by thermophoresis (t_T) against the time taken by wax particle to diffuse a length equal to its diameter by molecular diffusion (t_m) is presented in figure (9d). Since the plot points fall on their respective axis which are the trade-off boundaries, the objective functions attained optimal solutions at the complete expense of each other. Thus, they are independent on each other.

In figure (10a), the Pareto front of the time taken by wax particle to diffuse a length equal to its diameter by shear dispersion lies vertically on its axis beginning from a point above zero (0). Then the Pareto front of the time taken by wax particle to diffuse a length equal to its diameter by Brownian diffusion lies horizontally straight above its axis. This means that wax deposition time by shear dispersion was completely dominated by wax deposition by Brownian diffusion. Thus, wax deposition time by shear dispersion was fully saturated while wax deposition time by Brownian diffusion varied independent on deposition time by shear dispersion.

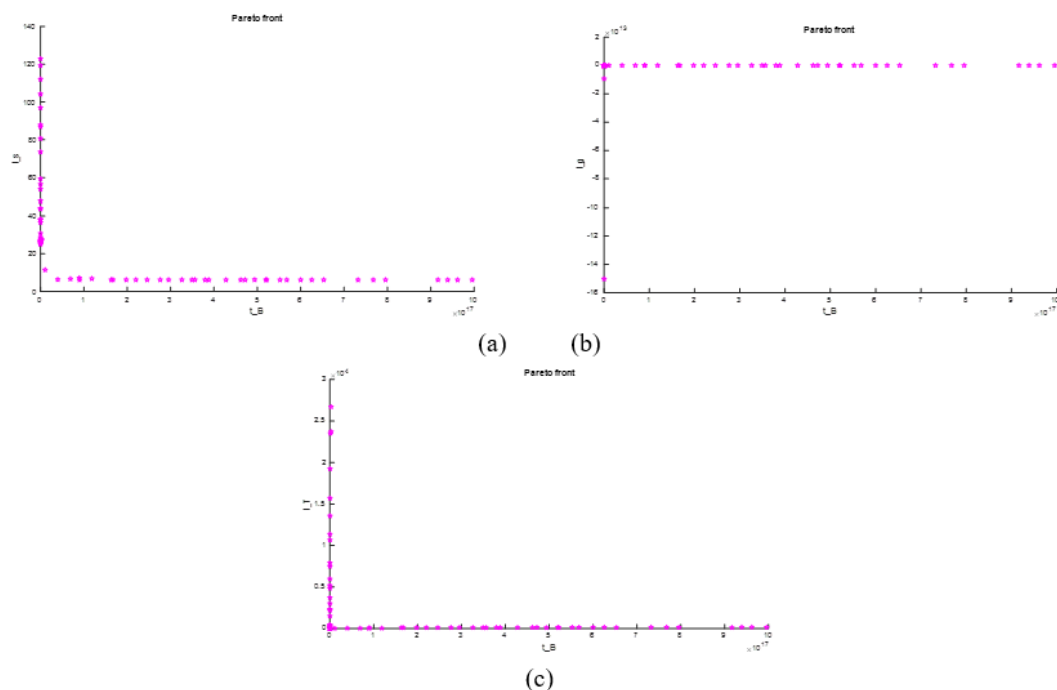


Fig. 10: Plot of Pareto Frontier of (a) t_s , (b) t_g and (c) t_T against t_B

Similarly, figure (10b) is the plot of Pareto front of the time taken by wax particle to diffuse a length equal to its diameter by gravity settling against the time taken by wax particle to diffuse a length equal to its diameter by Brownian diffusion. The plot showed that wax deposition by gravity settling was completely dominated by wax deposition by Brownian diffusion. This is indicated by the fact that the Pareto front of the time taken by wax particle to diffuse a length equal to its diameter lies on the vertical axis. Also, the solution set time taken by wax particle to diffuse a length equal to its diameter by gravity settling is constant, while the Pareto front of time taken by wax particle to diffuse a length equal to its diameter by Brownian diffusion varies along the axis.

The Pareto front of the time taken by wax particle to diffuse a length equal to its diameter by thermophoresis against the time taken by wax particle to diffuse a length equal to its diameter by Brownian diffusion is presented in figure (10c). The plot shows that their respective solution sets are mutually dominated, independent on each other and fully saturated. This is because the Pareto fronts lie on their respective axis.

The Pareto fronts of the times taken by wax particle to diffuse a length equal to its diameter by gravity settling and by shear dispersion are mutually independent on each other and mutually constant. This can be seen in figure (11a). They met each other at point slightly above zero (0).

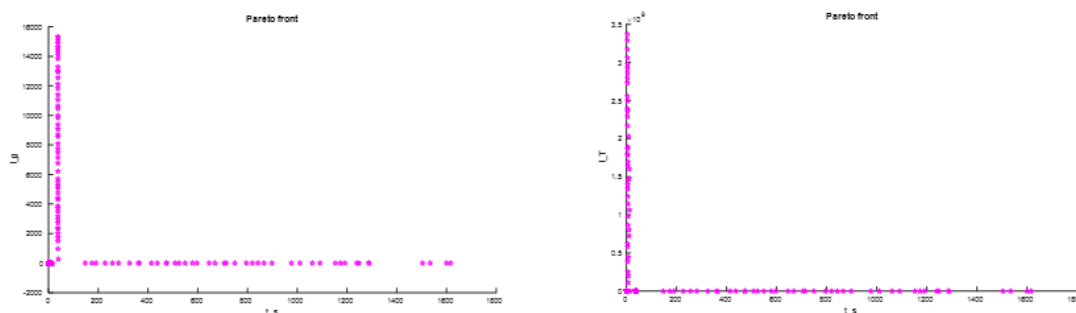


Fig. 11: Plot of Pareto Frontier of (a) t_g and (b) t_T against t_s

Figure (11b) is a plot of the Pareto fronts of the time taken by wax particle to diffuse a length equal to its diameter by thermophoresis and shear dispersion. The figure shows that the solution sets of both the time taken by wax particle to diffuse a length equal to its diameter by thermophoresis and the time taken by wax particle to diffuse a length equal to its diameter by shear dispersion are mutually saturated and mutually independent on each other.

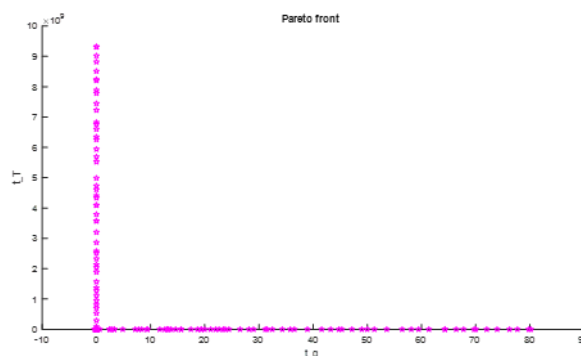


Fig. 12: Plot of Pareto Frontier of t_T against t_g

Finally, the solution set of the time taken by wax particle to diffuse a length equal to its diameter by thermophoresis dominated the solution set of the time taken by wax particle to diffuse a length equal to its diameter by gravity settling. Hence, while the Pareto front of the time taken by wax particle to diffuse a length equal to its diameter by gravity settling was fully saturated, the Pareto front of the time taken by wax particle to diffuse a length equal to its diameter by thermophoresis was varied from zero (0) point. This is shown in figure (12).

V. Conclusion

Paraffin wax deposition in onshore piping system is a known flow assurance challenge. It causes total blockage of the flow channels, reduces pipeline bore size and reduces heat transfer efficiency. These lead to production loss, reduced production efficiency and downtime. Therefore, in this research paraffin wax sample collected from a typical onshore production facility in Nigeria was studied in the laboratory to determine its thermophysical and transport properties. The key thermophysical properties determined are the melting point, the wax appearing temperature (WAT) and the flash point; while the transport determined are the liquid density, flow rate and viscosity. A further laboratory analysis was carried out to determine the molecular composition and characteristics of the wax sample. This showed the molecular mass, molecular formula, structural formula and characteristics of the wax sample.

The compositional analysis would help in the choice of the appropriate strategy in mitigating deposition of the paraffin wax in the piping systems. It was also noted that the wax sample composed of different aliphatic and aromatic hydrocarbons as well other derivatives. Thermal properties showed the range of thermal exposure to which the wax sample can be subjected in the course any thermal deposition mitigation strategy to achieve the desired results without any fire hazard. The transport properties would determine the necessary mechanical impact to mitigate its deposition in the piping systems. Also, the measured thermophysical and transport properties of the paraffin wax sample were implemented in the deposition mechanisms for metaheuristic evaluation.

Thus, results of the metaheuristic evaluation performed using the multi-objective genetic algorithms (MOGA) showed the range of times taken by wax particle to diffuse a length equal to its diameter by molecular diffusion, Brownian diffusion, shear dispersion, gravity settling and thermal diffusion (thermophoresis). This presented the score histogram and other plot functions that visualises the solution set of all the objective functions simultaneously. The score histogram shows the score diversity of individuals in the generation. It measures the difference that lies within the solution sets (individuals) and indicates that for 100 individuals, the best solution ranges. The score diversity is a graphical presentation of the distribution of the range of solutions of each objective function for the population of individuals. Other plot functions used for performance diagnostics are the average Pareto distance, selection function, average distance plot, rank histogram, average Pareto spread and the Pareto front. The average Pareto distance shows the average pairwise distance between solutions in the population at each generation, the diversity, convergence and stability of the solution set. Selection function plot shows plot of number of children against individuals and provides an understanding of how individuals are chosen from the population to reproduce and move towards better solution set. Average distance plot shows the distance between individuals in the population, between each solution set and the nearest neighbour or between solution set and a reference point. Hence, the distance to the Pareto front is small over generations, the population shows good convergence toward the optimal point; if it is large over generations, the algorithm may be struggling to find optimal solution set. The rank histogram, like other plot functions, visualizes the relationship between number of individuals and the different ranks. The bins of the histogram show number of individuals at each Pareto rank, and rank 1 has the highest number of individuals followed by rank 2 and so on. The average spread ranging from 0 to 1 plotted against the generation shows the distribution in each generation of about 500. This illustrates how many individuals that exist in each generation. The Pareto front plots show the relationship between conflicting

objectives and reveal how the algorithm balances them. Hence, an attempt to improve the solution set of any of the objective functions will worsen the solution set of the other objective function. Hence, the values of d (in m), μ (in Pas) is the fluid viscosity, V_{solute} (in $m^3 mol^{-1}$) is the molar volume of the solute at normal boiling point, ω (in s^{-1}) is the mean shear rate of suspending fluid, ρ (in kgm^{-3}) is density of the fluid, k (in W/mK), k_p (in W/mK) and ∇T the thermal gradient can be determined mathematically given the measured values of T (in K) is the temperature, ρ_p (in kgm^{-3}) is density of particle and M_w (in kg/mol) is the molecular weight. Based on this study, it takes more time to diffuse wax particle by Brownian diffusion and least time by shear dispersion.

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