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# A CASE-BASED SYSTEM FOR CONSTRUCTING A CONSTITUTIVE EQUATION FOR A VISCOELASTIC MATERIAL IN A LAMINAR FLOW

***S. M. F. D. Syed Mustapha***
Faculty of Computer Science and Information Technology
University of Malaya
50603 Kuala Lumpur, Malaysia
Fax: 603-7579249
Tel: 603-7696346
email: symalek@fsktm.um.edu.my

***T. N. Phillips***
Dept. of Mathematics
University of Wales, Aberystwyth, Penglais Hill
SY23 3DB, UK
Fax: +44 1970 622777
Tel: +44 1970 622769
email: tnp@aber.ac.uk

***C. J. Price***
Dept. of Computer Science
University of Wales, Aberystwyth, Penglais Hill
SY23 3DB, UK
Fax: +44 1970 622455
Tel: +44 1970 622444
email: cjp@aber.ac.uk

***ABSTRACT***

*The formulation of constitutive equation (model) is essential in order to simulate or predict the behavior of viscoelastic material in many complicated industrial flow processes. The generation of such model is tedious and time-consuming operation. The techniques of artificial intelligence (AI) have proven to be amenable to solving rheological problems. Several subsystems of these types have been built. They are the viscometric flow analyzer, static test analyzer and dynamic test analyzer. However, these subsystems are rather incompatible to each other and segregated. In this paper, we discuss how these subsystems can be integrated in an architecture whereby the communications between them can be controlled by a case-based system. We describe the problems commonly encountered during the experiment, the data analysis and the formulation of constitutive equation. It is then shown how the problems and solutions are presented as a case. A technique so-called model-guided repair is used for adaptation purpose in the case-based system. A schematic diagram of the architecture of the hybrid system is given in the final section.*

***Keywords:*** ***Case-based system, Viscoelastic materials, Model-guided repair, Rheology, Constitutive equation hybrid systems, Artificial intelligence, Rheological model***

## 1.0 INTRODUCTION

In rheology, fluid is characterized using a constitutive equation. The model is used to predict and simulate for other kinds of flow conditions. According to Barnes, it is reasonable to say that all materials in this world exhibit viscoelastic behavior [1]. Therefore, the study of such behavior is so essential. The mathematical description for viscoelastic fluid is much more complex than its Newtonian counterpart. In real application, the constitutive model does not only tell the relationship between the stress and strain but other rheological properties as well such as temperature dependency, time dependency, pressure-dependency, viscosity, etc. The determination of a specific constitutive model/equation for a given fluid and flow type is not a straightforward task. The complication begins mainly in understanding the flow process of a real application. A full grasp of understanding is essential for a complex process such as injection molding which has several subprocesses.

The motivation of this research is to employ an artificial intelligence (AI) technique in automating the task of formulating a constitutive equation. Several subsystems using this technique have been built. Among these are the viscometric flow analyzer which calculates the viscosity of a generalized Newtonian fluid in a laminar flow [2, 3], static and dynamic test analyzers, which calculate the relaxation or retardation times from static or dynamic experiments respectively [4, 5, 6, 7, 8, 9, 10]. The viscometric flow analyzer is applicable to inelastic fluid and the static and dynamic test analyzers are for more general linear viscoelastic material.

An intelligent program, which controls the internal communications between these subsystems and the external communications with the user, is needed. A case-based system is proposed to handle this task. This work shows a case-based system that aims to guide the user with the following tasks:-

1. *Experimental Set-up*: It begins with the type of experiments for the preparation of samples, selection of rheometers and geometries.
2. *Data Analysis*: It involves calculating the material parameters such as the shear viscosity, retardation or

relaxation times, extensional viscosity, normal stresses, die swell, etc.

3. *Constitutive equation or model*: It involves the selection of the relevant constitutive equation and its formulation.

## 2.0 PROBLEMS AND DIFFICULTIES IN CONDUCTING AND ANALYZING RHEOLOGICAL EXPERIMENTS

The kind of a scenario provided here reflects the problems and difficulty frequently encountered by an ordinary user. Ordinary users are those who work in industries and who do not receive enough professional training on the use of rheometers. There are many problems and potential difficulties that can be listed but only a few are mentioned here. The problems could be theoretical or practical ones that can be categorized as follows:

### 2.1 Experimental Set-up

There are many types of rheometers widely used but only two types are mentioned here. The characteristics of these rheometers are important for the users. The preparation sample prior to an experiment is also essential for the user to know.

*Deciding which rheometers to use*

The problems may even start when it comes to making a decision about which type of rheometer to purchase. Different rheometers have different significance and usage. The selection of a rheometer is always associated with the types of flow processes and rheological properties to be investigated. A controlled-shear-stress rheometer is more appropriate in studying the yield stress value of a material [11]. A controlled-shear-rate rheometer is applicable to semi-solid materials. An excellent review of the disadvantages and advantages of rheometers and geometries is given by Ferguson et al [12] and Jones [13, 11].

*When to use capillary rheometer*

If the industrial process involved is an extrusion or injection molding process then the capillary rheometer is more suitable. Capillary rheometers can also simulate laminar flow [12]. Another factor is that the capillary rheometer can run at higher shear rates than its rotational rheometer counterpart. Other flow situations such as die swell or melt fracture studied by rheologists in laboratories require capillary rheometers to be used. There is more than one type of capillary rheometer. They are the controlled-shear-rate and controlled-shear-stress types [11]. For fluids such as suspensions whose flow is prone to instability such as the plug flow then a controlled-shear-stress rheometer is more appropriate [12]. The controlled-shear-rate capillary rheometer is used to prevent the occurrence of melt fracture of polyethylene [12]. The controlled-shear-rate capillary rheometer is also suitable for a constant flow rate process such as jet extrusion or fiber spinning.

*Choosing geometry*

The choices of geometry depend on the purpose of the observation and the fluid to be used. For example, the occurrence of 'fracturing' [12] can easily be observed in cone and plate rather than concentric cylinders. The concentric cylinder is recommended for low viscosity fluids (<10 Pa.s).

*Experimental procedures*

Sample preparation is essential for some materials such as polyesters and polyamides, which are prone to degradation by the effect of hydrolysis [12].

### 2.2 Rheological Measurement

If one is engaged in an industrial process and intends to know which kind of rheological measurements are needed, then three levels of knowledge are required, as depicted in Fig. 1. Level 1 gives the type and the characteristics of the flow process (e.g. fiber spinning or injection molding). In Level 2, an association of the characteristics of the known flow process with the possible material or flow parameters is needed (e.g. shear viscosity, normal stress or die swell). Level 3 is required to determine which rheological measurements or experiments will reveal information needed in the Level 2 and which experiments need to be run in order to obtain the shear viscosity, the normal stress and the die swell, etc. It is also important to realize that, as shown in Level 2, the criterion, in deciding which material or flow parameters to investigate, are characteristics of material's behavior. The characteristics of the flow process also play a role in deciding how to conduct the rheological experiments. We illustrate this with some examples.

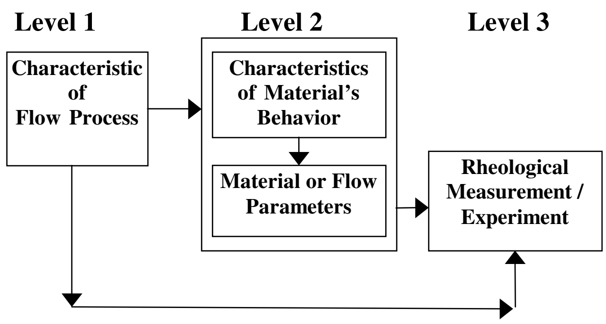


Fig. 1: Three levels in determining rheological experiments

*Examples for Level 1*

The characteristics of a flow process describe whether the flow involves high strain rates, thermal properties (heat dissipation) - isothermal or nonisothermal, high pressure (pressure-driven flow) or low pressure (gravity-driven flow) etc. Other factors such as wall effects, boundary conditions, steady and unsteady flows are also relevant.

*Examples for Level 2*

The general rule is that if a material does not exhibit a certain behavior or property in any circumstances, then there is no reason to investigate that behavior. A paste does not exhibit elongation, so considering paste in an extensional flow in order to investigate extensional viscosity is meaningless [14].

*Linkage of Level 1 and Level 2*

The relationship between the flow process (manufacturing process) and the material or flow parameters described by Ferguson [15] is shown in Fig. 2. The direct connection shows that a flow process such as injection molding will require information on shear viscosity, extensional flow, relaxation times, and viscosity and temperature relationship that is to be investigated. Other connections also apply to other flow processes. However, in Level 2, it was mentioned that the material's characteristics must also be considered in determining whether the material or flow parameters are relevant or not. So, even though extensional flow is a required parameter for injection molding, it may not be investigated if it is irrelevant to the characteristics of the material.

*Linkage of Level 2 and Level 3*

The next stage is to know the relationship between the material or flow parameters and the rheological measurements (Fig. 3). The connections show that there could be more than one experimental method that can be used in getting a material or flow parameter. For example, a user can run a viscometric flow experiment or Poiseuille flow using a capillary rheometer to calculate the shear viscosity.

*Linkage of Level 1 and Level 2*

The information from Level 1 is also taken into account before running the rheological experiment. For example, information such as the temperature, time and pressure used in the flow process is also required in order to simulate closely with the experiment.

## 2.3 Constitutive Equation

So far we have discussed two types of problems frequently encountered by users, namely the experimental set up (i.e. choosing rheometers, geometries and sample preparation) and rheological measurements. Another kind of problem, which is important, is to select the most appropriate constitutive equation from among the ones available. For every type of flow regime such as the steady shear flow, small-amplitude flow (linear viscoelasticity) and nonlinear viscoelasticity flow, there are many constitutive models already available. Among these models, there is one specific model that is the best to represent a range of data set for a particular flow problem. The reason is that each model has different advantages and disadvantages. For example, the Power Law model is frequently chosen for being simple to use and requires only two unknown parameters. However, this model has a limitation in that it cannot be used in the first and second Newtonian regions.

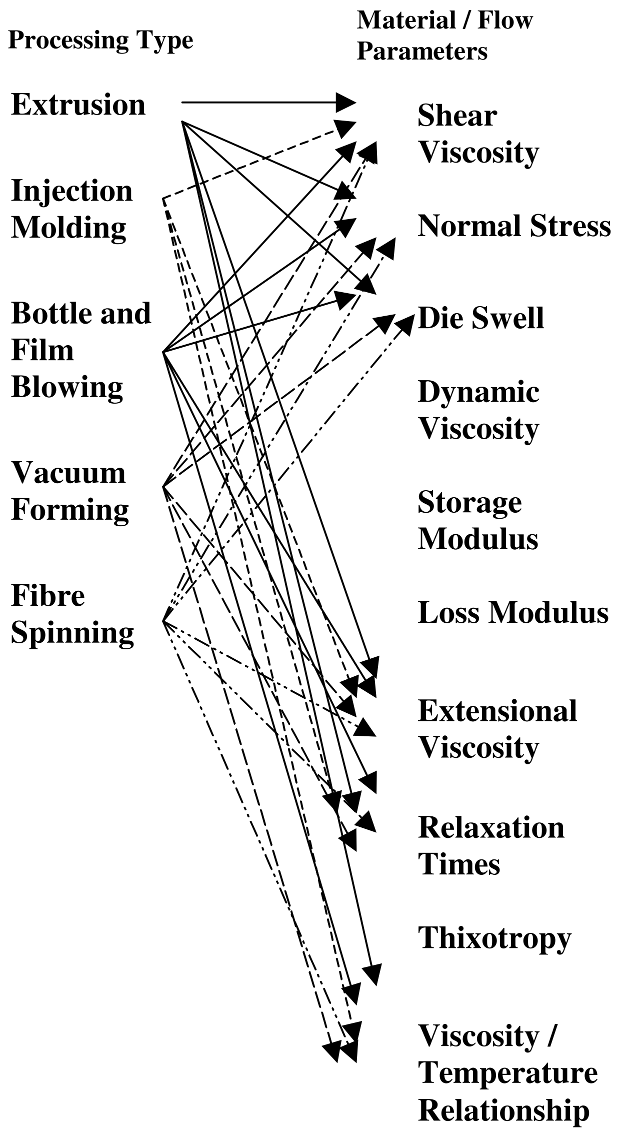


Fig. 2: The relationship between the flow process and the material or flow parameters

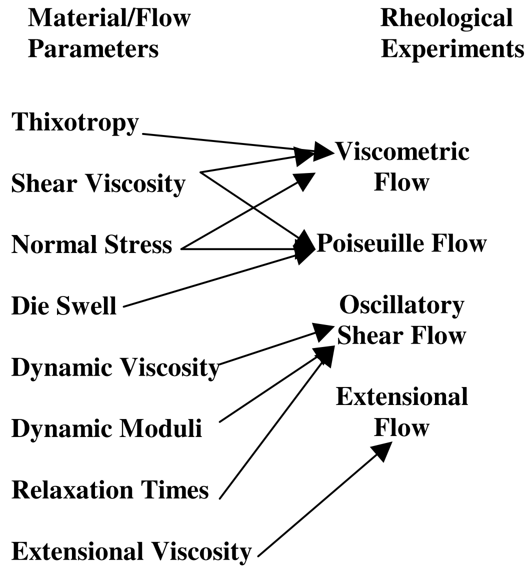


Fig. 3: The relationship between the material parameters and rheological measurements

The Carreau -Yasuda model has a larger span of shear rate range than the Power Law model such that it can cover the region of Power Law and also both the first and second Newtonian regions. The disadvantage of this model is that it has four adjustable parameters, which are more difficult to handle. The selection of a constitutive model also depends on the characteristics of the fluid and flow. For some fluids, the characteristics are found to be dependent on thermal conditions and pressure. In this case, the constitutive equation used must then be combined with the thermal or pressure relationship. For example, the modified truncated Power Law and Carreau-Yasuda models, after considering thermal relationship respectively, are as the following [16].

$$\eta(\dot{\gamma},T)=\begin{cases}\eta_0(T_0)a_T & (a_T\dot{\gamma})<\dot{\gamma}_c\\ \eta_0(T_0)\left[\dot{\gamma}/\dot{\gamma}_c\right]^{n-1}a_T^n & (a_T\dot{\gamma})<\dot{\gamma}_c\end{cases}$$

and

$$\eta(\dot{\gamma},T)=\eta_0(T_0)a_T\left[1+\left(a_T\,\dot{\gamma}/\dot{\gamma}_c\right)^2\right]^{(n-1)/2}$$

where $a_T$ is a shift factor. The viscosity models are not only instantaneous to the shear rate but also to the temperature. The characteristic of the flow process may contribute towards the formulation of the constitutive equation such as the occurrence of secondary flow, slip, boundary conditions (fixed or free), etc.

The above discussion shows that a deep knowledge of rheology (theoretical and experimental) is essential from the outset of experiment to the modeling process. The knowledge required could be summarized as follows: -

1. The knowledge of manipulating experimental instruments such as rheometers, geometries and sample preparation.
2. The knowledge about the behavior of a fluid used in the experiment such as having elongational properties, temperature or pressure dependencies.
3. The knowledge of the flow processes in the industry whether they involve high strain rates, isothermal condition, slips, etc.
4. The knowledge of using and choosing the most appropriate constitutive equation. Examples given previously are the viscosity models.

Knowledge like this is gained through experience and a deep understanding of rheology, which not many people possess. An important issue is how these four kinds of knowledge are related to each other and what kind of expert reasoning is involved in the process of solving these problems. We will now discuss how techniques in artificial intelligence can be used in modeling the reasoning process practised by rheologists.

## 3.0 MODELING THE REASONING PROCESS ON THE FLUID, PROCESS FLOW AND CONSTITUTIVE EQUATION USING CASE-BASED SYSTEM

A case-based system is a retrospective system, which replicates the natural way of solving problems by humans. Several past cases are retrospected and compared in order to find an identical case. If a matching case is found then the suggested solution will be used for the new solution.

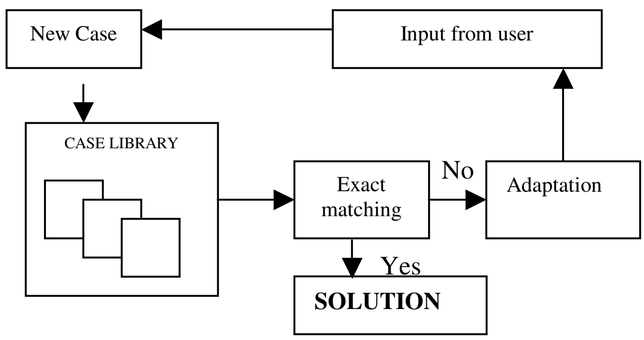


Fig. 4: A general view of a case-based reasoning system

If the matching is not exact but partially matched, then the solution can be obtained by adjusting the old solution It needs to be emphasized here that the reasoning process to be modeled is to help users to choose the most appropriate constitutive equation for a specific fluid and flow process.

A typical case-based system is illustrated in Fig. 4. The values of the new case are instantiated interactively from the user's local information. The user enters the key features of the new case as an input to the case-based system. Examples of the important key features for a fluid will be like the class of fluid (polymer melt or suspension), temperature dependence and so forth. Similarly, the key features for the flow process will be the characteristics of the flow. Some of the key features can be obtained by default from the case library. All of this information is used to construct a new case.

### 3.1 Representing a case in the case library

A case contains three major components: a problem or situation description, a solution and an outcome. The system uses the information described in the situation or problem component to evaluate the match between the old and new cases. The new solution is taken straight from the old case if the match is exact otherwise an adaptation process begins [17]. The outcome reveals whether the solution given is successful or not.

We show an example of a case representation below.

**Example:**

**CASE A**

**SITUATION DESCRIPTION:**

Flow Characteristics:
Process: Transporting Polymeric Fluid in a Circular Tube
Thermal Properties:
Temperature: Isothermal
Heat Dissipation: None
Flow Type: Laminar
Flow Driven By: Pressure
Effects:
Inertia: Negligible
Wall: None
Slip: None
Elongational Flow: None

Maximum Pressure To Be Used In Tube: 10.26 Pa

Geometry of Flow Process:
Shape: Circular Tube
Length: 0.12 m
Radius: 0.005 m
Material Characteristics:
Material Type: Polymer Melt
Material Name: LDPE
Density: Unknown
Temperature Dependency: Yes
Pressure Dependency: None
Elongational Properties: Yes (Strain Thinning)
Molecular Weight: Unknown

Constitutive Equation Characteristics:
Shear Rate Dependence of Viscosity Model: Yes
Pressure Dependence of Flow Rate Model: Yes
Temperature Dependent model: Not Needed

**SOLUTION:**

Experimental Set Up:
Flow Type: Steady Shear Flow
Rheometer Type: Controlled Shear Stress
Geometry Type: Concentric Cylinder
Temperature: Isothermal $20^0$C
Time Range: 120 s
Shear Stress use: 0.2139 Pa
Sample Preparation: Not Needed

Data Analysis:
Graph Plot: Shear Stress vs. Shear Rate
Graph Format: Log-Log
Numerical Method: Linear Least Squares

Constitutive Equation:
Viscosity Model (Shear Rate Dependent): Power Law, Herschel-Bulkley, Sisko and Casson
Flow Rate Model: Power Law, Casson and Sisko

**OUTCOME:**

Model Use: Power Law
Shear Rate Range: 3.596 - 727.2$s^{-1}$
Correlation: 0.9983
Yield Stress: None
Taylor Vortices: Exist (871 – 732$s^{-1}$)
Curve Type: Down Curve
Fluid Behavior: Shear Thinning
Power Law Index (n): 0.8032
Flow Rate Model Use: Power Law

$$Q = \left(\frac{n\pi R^3}{3n+1}\right)\left(\frac{RP}{2LK}\right)^{1/n}$$

Flow Rate at the end of the tube: 0.0822 $m^3$/s

In the situation description in Case A, there are three major key features being used. They are the flow characteristics, material characteristics and constitutive equation characteristics. They are strongly related to each other such that any changes to the new solution will require consideration of the three characteristics.

The section on flow characteristics of Case A describes that the flow involves transporting material in a circular tube under a laminar flow. The geometrical values such as the radius and length of the circular tube are also given. The material's name and type are vital in the reasoning process besides the other features such as temperature dependency, pressure dependency and so forth. The density and molecular weight are not known or irrelevant for the reasoning purpose. The formation of the constitutive equation in Case A requires the use of models which incorporate a shear-rate-dependence of the viscosity and pressure-dependence of the flow rate. The temperature dependent model is not needed since the flow is isothermal.

In the solution section of Case A, the three important tasks, which were mentioned in Section 1.0, are given. The experimental set up section recommended the user to run a steady shear flow experiment using a controlled-shear-stress rheometer. The concentric cylinder is used for this type of fluid. The temperature used is constant and the experimental time is about two minutes. The initial shear stress imposed is obtained from the following formula:

$$\text{Stress Use} = R/2\ \Delta P$$

where R is the tube radius and $\Delta P$ is the pressure drop (difference). The sample does not require any preparation prior to running the experiment. The data analysis requires a linear least square method to be used in the model-fitting. Several viscosity models are recommended to determine the viscosity of the fluid.

Finally, the outcome gives a more specific result to the problem than the one in the solution section. The Power Law model is chosen since it gives the highest correlation for the particular shear rate range compared to other models. The parameter values of the model are given to show how the flow rate is calculated.

There are several ways to represent the information in Case A in a computer. The scheme of representing this information is called the knowledge representation. Among these are the frames and slots, semantic network, predicate logic and others [18]. There are also other CBR (Case-Based Reasoning) shells and tools [19].

### 3.2 Adaptation

Adaptation is the process of modifying the structure in the solution by quantifying the discrepancies between the old and the new cases. There are several methods used in adaptation. Among them are substitution, transformation, special-purpose adaptation and repair and derivational replay [17]. Each of these methods has advantages and disadvantages. We shall not discuss all of them here, just the ones that are relevant to our problems. Adapting a new solution from old cases frequently manifests two kinds of situations. They are the following: -

1. Equivalent framework: The framework of the problem and solution of the old and new cases are the same. An example of this is that if a new Case B has the same problem description as Case A apart from a different length and radius of the geometry used, then the solution structure of Case B will be the same as Case A. (Note: This will not always be true for all items. This will be discussed later)
2. Partial framework: The problem descriptions in the old case have a different number of items than the new case. This situation most frequently occurs when extra constraints or conditions are imposed on either the old or new case. For example, the new case may have flow effects which do not appear in Case A.

For some application domains in which the old case has the equivalent framework of the new case, the substitution method is used for adaptation. However, a blind substitution to some items without realizing the impacts and side effects of the others is very risky. For example, a single change from a material, which does not require sample preparation to one, which does, requires the solution structure to be extended to include the preparation procedure. On the other hand, if we substitute the length and radius of the tube to some other values then only the shear stress used in the solution needs to be recalculated. A substitution of this kind does not affect the structure of the solution.

A situation where the framework of the old and new cases is not fully (partially) matched requires some items to be added, removed and substituted either in the old or new cases. Items are added when new evidence or facts are found based on existing information. For example, by knowing a material to be a type of polymer melt, a statement to say that it may possess viscoelastic properties can be added. An item such as molecular weight can be removed since it contains no useful information and may be an unrelated feature to the new case. Substitution in this situation can be similar to the situation when the substitution made can affect other items. Substituting the material type and flow process can cause changes to rheometer type and shear rate prescribed in the solution.

So, in our adaptation problem, a substitution method cannot be used independently in a situation where the descriptors in the old and new cases are not the same or when substituting a single item causes multiple impacts on other items. The second type of adaptation is the transformation method. A model-guided repair is a kind of transformation method we select to solve our problem.

*Model-guided repair*

This method depends on a causal model, which describes the causal relationship of several systems and situations [17]. In our problem, we need a relationship model which guides the adaptation process in adding, deleting and substituting items. The models consist of the characteristics of the systems that need to be described. The corresponding items of two or more characteristic models are compared and analyzed to see if repairing operations such as deletion, addition or substitution is conceptually feasible. We will elucidate this idea in detail later.

Model-guided repair is composed of three steps: -

1. Identify and list the differences between the old and new cases.
2. Analyze the discrepancies and characterize them.
3. Assign each discrepant item an appropriate model-guided repair heuristic.

Step 1 will select the items from the old and new cases when they are different by quantity (Q) (numeric or symbolic) or relevancy (R) of the item descriptors. This is immediately followed by Step 2 that is to label the differences. We show these two steps in Table 1. In Step 3, repair heuristics are used to decide whether to add, remove or substitute the items. Table 2 shows the application of the repair heuristics.

Table 1: Discrepant items selection and labeling them

| **CASE A** | **CASE B (New Case)** | **Labeling**<br>Q: Quantity<br>R: Relevancy |
|---|---|---|
| 1. Maximum pressure to use: 10.26 Pa | Maximum pressure to use: 50 Pa | Q (numeric) |
| 2. Process: Transporting polymeric fluid in circular tube | Process: Injection Molding | Q (symbolic) |
| 3. Material's name: LDPE | Material's name: HDPE | Q (symbolic) |
| 4. Elongational properties: Yes | - | R |

Table 2: Repair heuristics for discrepant items

| Item No. | Repair heuristics |
|---|---|
| 1 | Substitute |
| 2 | Substitute |
| 3 | Substitute |
| 4 | Add |

Fig. 5 shows the process of utilizing the characteristic model in deriving a solution of what alternative geometry to be replaced. The two inputs for the characteristic models are the fluid and flow models. The HDPE polymer melt can be used at higher shear rates, which satisfies the condition of the flow process in injection molding. The only rheometer, which is more suitable for this purpose is the capillary rheometer. So, this type of rheometer is recommended to the user.

The characteristic model can also be used to identify whether the items need to be added to a case or removed. One of the characteristics of HDPE is to show elongational viscosity. So, the item descriptor of elongational properties will be added to Case B after reference to the characteristic model of the fluid.

Using the model-guided repair method, substituting, adding and removing items have modified the structures of the problem or situation descriptors. Another interesting part is that the new solution can be projected based on the domain theory model. This means, some solution can be given even when information in past cases is not available. This method is more efficient than purely substitution methods such as reinstantiation, parameter adjustment, local search, query memory etc. which are not guided by the domain theory model. The idea of using a model such as the causal or characteristic models to guide the repair in the problem and solution has made the adaptation process more intelligent and robust.

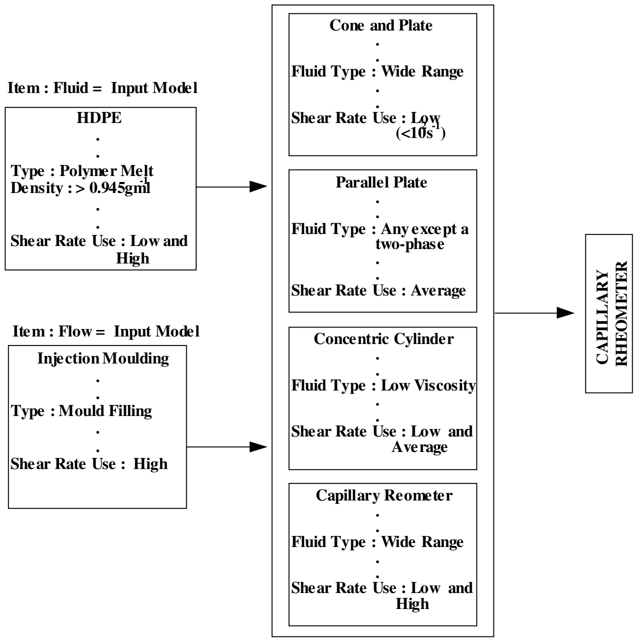


Fig. 5: The characteristic model of the fluid, flow process and geometry

## 4.0 THE INTEGRATED SUITES

Using a single mode of reasoning approach in solving multi-faceted and wide-range of application problems is not always possible. The reason is simply that each of the approaches has its own specific task, which it handles better than the others. For example, model-based reasoning that emphasizes reasoning from the first principles has been shown to solve the expert system's knowledge acquisition bottleneck problem but is mostly inappropriate for application problems, which lack fundamental theory [25]. That is a situation where theoretical models that represent the physical behavior from a set of observations are very vague or nonexistent. Maintaining a knowledge-based system or rule-based system becomes unmanageable when the set of rules are extremely large, even though removing and adding them (rules) is easy at an early stage [26]. However, special capabilities demonstrated by each of these reasoning entities can be combined to support each other as a single hybrid system. The integrated computing paradigm has also shown to be implemented by many authors especially with the case-based reasoning system. Among them are the integration of case-based reasoning with model-based reasoning [20] and rule-based systems [21, 22]. In this section we will discuss:-

1. Components of the integrated suites and the functionalities.
2. Traditional and automated processes in determining constitutive equations for a fluid in a flow geometry.

Fig. 6 is provided for this discussion and to illustrate the overall view of the integrated suites.

### 4.1 Components of the Integrated Suites and the Functionality

*Classification of the Expert's Knowledge*

The interactions between the expert and user involved three types of knowledge. In studying artificial intelligence, these types of knowledge are termed declarative knowledge, meta knowledge and procedural knowledge [18]. Declarative knowledge is a concept or fact. Meta knowledge is knowledge about the knowledge or fact about the fact. Procedural knowledge is knowledge about how to perform tasks.

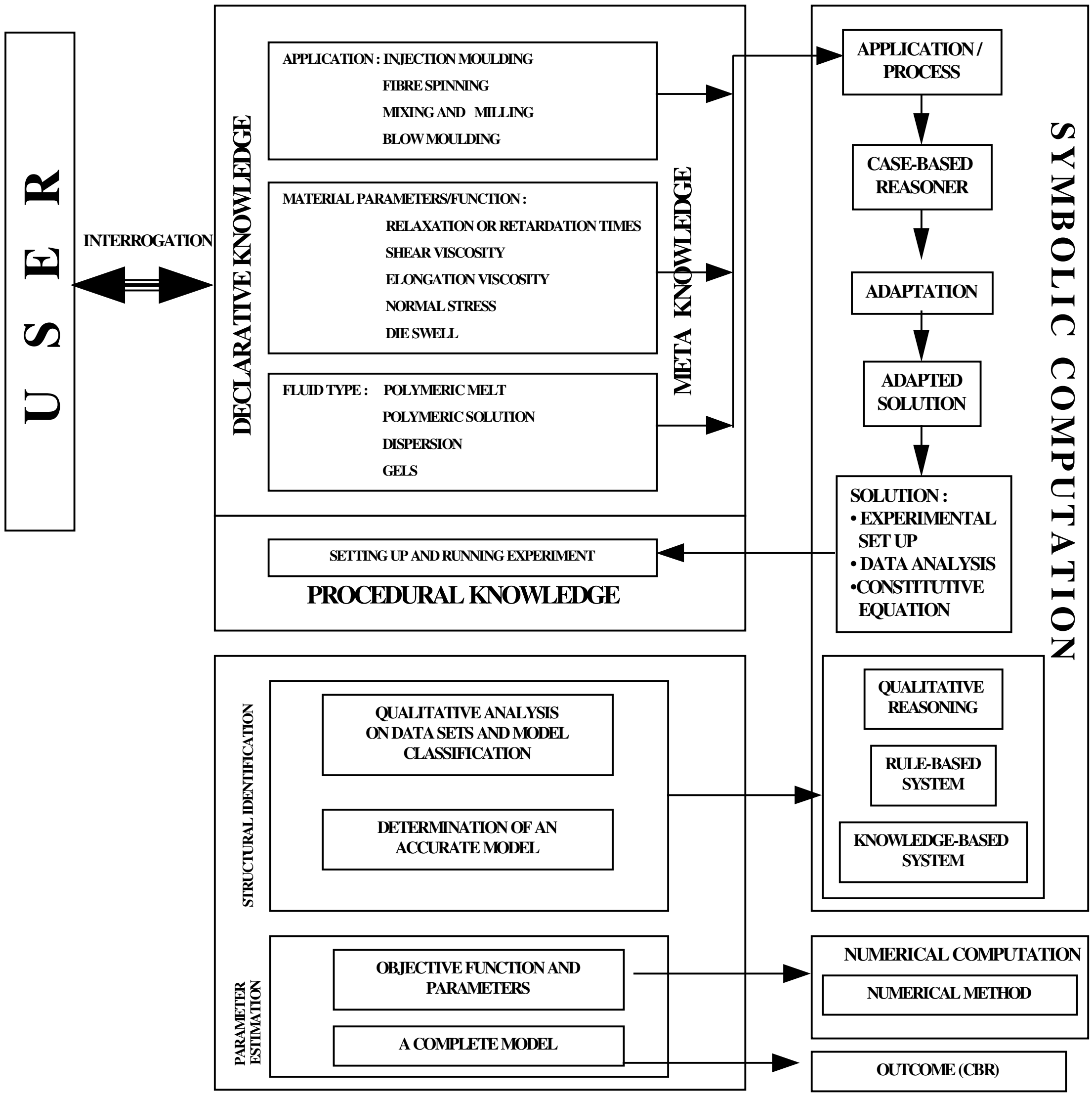


Fig. 6: A design of a hybrid system in determining a constitutive equation of a material in a flow process

*Symbolic and Numeric Computation*

The systems that are categorized as symbolic computation are the case-based reasoning system, qualitative reasoning system, rule-based or knowledge-based systems. The declarative, meta knowledge and procedural knowledge can be encoded into these systems. This type of computation is used in performing symbolic processes such as gathering information from the user, giving instructions and explanations to the user and also symbolic inputs to other systems.

Statistical reasoning such as curve fitting, parameter estimation and other numerical techniques are classified as numerical computation. It is used to determine the exact numerical values of the material parameters for the constitutive equation.

*Case-based Reasoning System*

It is responsible for managing information obtained from the user, matching to previous cases to adopt the solution from an old case or through an adaptation process.

*Qualitative Reasoning System*

A reasoning technique, which has been used intensively in the qualitative interpretation of rheological data. Qualitative interpretation has been used, for example, to determine the value of the logical triplet associated with the output from a creep experiment [4, 5, 6, 7].

*Rule-based and Knowledge-based systems*

A rule-based system represents a piece of information in the following format:

If <condition> then <conclusion>

A knowledge-based system is a system whose performance depends on the amount of knowledge it has [18]. The heuristic rules used in labeling different segments of the graph described in this project are produced by these systems.

### 4.2 Traditional and automated processes in determining constitutive equation for a fluid in a flow

In order to illustrate clearly the process involved in the integrated suites, we demonstrate a simple example beginning from the stage of eliciting the user until the derivation of constitutive equation. In parallel, we show how components of the integrated suites are involved in supporting reasoning around the system.

*Human Expert*: What kind of flow process you are looking for?

*System*: [A menu or list box of application processes such as injection molding, fiber spinning, mixing and others is shown for the user to select]

*User*: Injection molding

*Human Expert*: Which step of injection molding you are interested in: mold filling, packing, holding and cooling? [23]

*System*: [Using meta rules or meta knowledge to direct the relevant questions to the user. Declarative knowledge tells the system that mold filling, packing, holding and cooling are the steps in the process of injection molding]

*User*: Cooling [User selects answer by highlighting the item in the listbox]

*Human Expert*: [The expert tries to retrieve or recall previous cases that are related to cooling system in the injection molding process. When a similar or partially match case is remembered, the expert will ask more questions for further actions]

*System*: [At this stage CBR system is used to browse previous cases in the case library. If a similar or partially matched case is found, then further questions may be required in order to fill in the values of the items in the new case]

*Further questions can be something like these.....*

*Human Expert or System*: Is the temperature in the cavity constant (isothermal)?

*User*: Yes

*Human Expert or System*: Time or duration of cooling?

*User*: 10s

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•
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*Human Expert*: [Having sufficient information from the user, the expert will try to generate a new solution based on the matched old case or restructure the solution if needed. In this example, the expert will advise the user to investigate the stress relaxation times. This is because the relaxation stress starts when the flow is stopped [23].

*System*: [The CBR system uses the adaptation method and characteristic models of the flow process, fluid and constitutive equation to form a procedural knowledge which tells the user how to setup an experiment and which experiment to run. The solution of the CBR system also advises the user how to analyze the data and provide a range of constitutive models for the user to consider in characterizing the data (we have shown the details how this may happen in the examples from previous section).

What we have shown so far are the interactions between the expert and the user. In the automation process, the expert is replaced by the CBR system and also the rule-based representation which consists of declarative and meta knowledge.

The automated system which has already been built in [2, 3, 9, 10] is related to the two system blocks (Fig. 6), namely, structural identification and parameter estimation. The work described by Capelo et al as well as Mustapha [2, 3, 4, 5, 6, 7, 9, 10] share two principles:-

1. Using qualitative reasoning technique to eliminate misfit models. This is called structural identification [24].
2. Model fitting will be performed on the potential models to the specified data range in order to obtain material parameters. This is called parameter estimation.

We provide brief examples on the determination of viscosity models and discrete relaxation spectra to compare the similarities in Fig. 7.

***Structural Identification:***

Fig. 7(a) shows that the viscosity model can be classified according to the shear rate range it can cover and also its behavior with respect to shear rate. Use of qualitative reasoning techniques can do this.

(a) Viscosity graph model (b) Linear viscoelasticity graph model

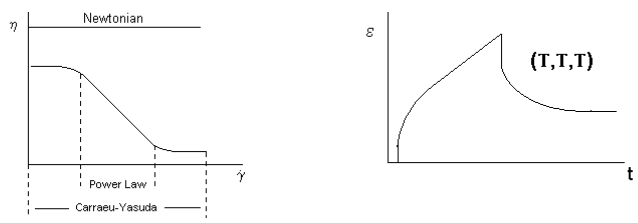


Fig. 7: A similarity comparison between the analyses on viscosity models and linear viscoelasticity models

Qualitative observations can be made on the slope (to see whether the viscosity increases, decreases or is independent of shear rate) and also the span of the shear rate [2, 3]. The former is used to differentiate between the Carreau -Yasuda and Newtonian models whereas the latter is used to differentiate between the Carreau-Yasuda and Power Law models. So models that have similar kinds of qualitative observations within the given data range will be selected.

Fig. 7(b) also shows that the elimination of irrelevant classes of models can be made using qualitative techniques by observing the qualitative features of the segmented graph. The determination of linear viscoelasticity models using qualitative reasoning technique has been discussed by Capelo et al and Mustapha [4, 5, 6, 7, 8, 9, 10].

***Parameter Estimation***:

The shear viscosity is the material parameter produced by the viscosity model while the linear viscoelasticity model produces relaxation or the retardation spectra. An accurate model can be formulated by choosing the model that gives the best fit and satisfies specified criteria of the model fitting.

It is believed that if this work is extended to other flow regimes such as nonlinear viscoleasticity, then the two principles can also be applied. The reason is simply that every model is formulated to overcome the shortcomings of others and as has already mentioned, the constitutive models are not made to be universally applicable to all fluid and flow situations.

## 5.0 CONCLUSION

The work shown here is a vigorous attempt to integrate the existing subsystems already developed. To do this, it is important to generalize the analysis techniques of many rheological experiments. We have outlined the generic steps in the previous section. The design of integrated suites has made us realize that regardless of the flow regimes, the determination of an existing constitutive equation for a certain flow and fluid can be made in two main procedures. They are the structural identification: qualitative analysis on graph behavior in order to determine the class of model and, parameter estimation: statistical analysis in order to formulate a complete model.

Case-based reasoning technique provides a faster solution in the knowledge acquisition than its expert system counterpart. In rheology, the process of constructing rules is not simple since the same material can deform in different manner under separate flow conditions. Thus, same models are not always being used for the same materials. Large amount of heuristic rules is required to govern the generation of models if expert system is used. In case-based system however, a set of models can be generated easily from the solution if cases matched. For a new case, which has an exact or partial match, the solution can be produced or adapted. Cases are tackled individually. Therefore, the process of developing cases in case-based system will be faster than rules in expert system.

Adaptation is the most crucial part in the process of matching. We have chosen model-guided repair as a suitable adaptation tool. This tool allows consideration of two cases in a more conceptual manner.

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## BIOGRAPHY

**S. M. F. D. Syed Mustapha** obtained his Master and Ph.D. degrees from University of Wales, UK. Currently, he is a lecturer in the Faculty of Computer Science and Information Technology in the University of Malaya. His research interests are rheology, expert system, case-based reasoning, qualitative reasoning and model-based reasoning.

**T. N. Phillips M.Sc DPhil (Oxon)** is a reader in Department of Applied Mathematics in University of Wales, Aberystwyth. His expertises include rheology, spectral methods, computational fluid dynamic, numerical linear algebra and domain decomposition techniques.

**C. J. Price** is a senior lecturer in Computer Science Department in University of Wales, Aberystwyth. His expertises are in failure mode effect analysis (FMEA), case-based reasoning and model-based reasoning.