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An agent-based method for simulating porous fluid-saturated structures with indistinguishable components

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HIGHLIGHTS

- A hybrid agent is developed to represent single-phase porous structures.
- The hybrid agent is capable of intra-agent evolution.
- Intra-agent rules are presented to control evolution of the hybrid agent.
- Patterns similar to the porous single-phase structures are generated.

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ABSTRACT

Single-phase porous materials contain multiple components that intermingle up to the ultramicroscopic level. Although the structures of the porous materials have been simulated with agent-based methods, the results of the available methods continue to provide patterns of distinguishable solid and fluid agents which do not represent materials with indistinguishable phases. This paper introduces a new agent (hybrid agent) and category of rules (intra-agent rule) that can be used to create emergent structures that would more accurately represent single-phase structures and materials. The novel hybrid agent carries the characteristics of system's elements and it is capable of changing within itself, while also responding to its neighbours as they also change. As an example, the hybrid agent under one-dimensional cellular automata formalism in a two-dimensional domain is used to generate patterns that demonstrate the striking morphological and characteristic similarities with the porous saturated single-phase structures where each agent of the "structure" carries semi-permeability property and consists of both fluid and solid in space and at all times. We conclude that the ability of the hybrid agent to change locally provides an enhanced protocol to simulate complex porous structures such as biological tissues which could facilitate models for agent-based techniques and numerical methods.

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1. Introduction

Agent-based methods (ABM) are discrete approaches where the interactions of autonomous entities, called agents, create diverse complex behaviours of a system [1–3]. Agents as micro-scale elements of an agent-based structure are identified by their states where each state represents one of the constituents of the system. Numbers (e.g. 0 and 1) or colours (e.g. black and white) may be used to demonstrate states of the agents [4,5]. Interactions between agents are determined by decision rules which can be deterministic [6], probabilistic [7,8] or change over iterations as a result of learning from previous steps (learning automata) [9,10]. ABM has been successfully used to create patterns which can be representative of multi-component structures such as porous materials [11,12] where relations between agents at the extra-agent environment is determined by local rules. Although the state of the agents can be changed and an agent can be converted to another agent, for example, 0 is changed to 1 which is representative of another element of the system, current rules affect systems in inter-agent scale by changing agents' arrangements in the system. Therefore, the system can be argued to operate like mixtures of distinguishable components where the structure contains agents which are representatives of one component at a time. For example, the structure of a saturated porous system is created by mixing solid and fluid agents. However, this is unlike the situation in single-phase multi-component materials such as many biological systems, where the constituents are intermingled at the molecular level [13,14], and consequently elements of the system at any level (size) consist of practically inseparable components.

The philosophical premise of the work reported in this paper is the notion that in order to create appropriate models to study the microscale responses of multi-component single-phase materials, a representative structural model is required. This paper introduces an enhanced agent that can be used to create multi-component single-phase materials and structures. This new agent can use some of the established simple neighbourhood rules as well as new intra-agent rules that will be developed in this paper. We introduce an approach that combines both intra- and extra-agent rules to create representative structures that can idealize single-phase, fluid-saturated semi-permeable materials.

2. Material and methods

The novel approach and methodology involving the concept of combining simultaneous local (intra-element) and global (inter-element) responses where a system's emergence is determined by two innovations, a novel enhanced hybrid agent and new intra-agent rules.

The Hybrid agent: This agent contains within it the system constituents. This agent carries properties of all constituents where the characteristics of the agent are a combination of all imposed behaviours. A hybrid agent is identified by its constituents and their quantities which define the state of the hybrid agent. The constituents can be physical components such as materials, or abstract properties such as attributes or a combination of both. It is not necessary for the quantities of the constituents of a hybrid agent to sum to one. For example, if a system consists of customers and sellers, each hybrid agent includes both customer and seller. When a seller purchases an item for himself, he is a customer because he purchased the item and paid for it, while he could simultaneously sell the item as a seller. Therefore in this situation, an agent must carry attributes of a customer and a seller at the same time.

A hybrid agent is capable of changing within itself in time. The intra-agent evolution of the hybrid agent may be indicated by changing quantities of the constituents within the agent. In order to determine gradual intra-agent changes of the hybrid agent, a new category of rules is required.

Intra-agent rule: This is a new intra-agent control mechanism which enables intra-agent evolution of the hybrid agent. Although a hybrid agent can interact with its neighbours based on extra-agent rules such as traditional neighbourhood rules, an intra-agent rule is required to determine change within the agent. Extra-agent rules determine relations between agents, often involving time-dependent spatial rearrangements of the agents in the system, while intra-agent rules define how a hybrid agent evolves. As intra-agent rules are applied to the agents in the system individually, the intra-agent evolution of each hybrid agent is distinct from or independent of other agents in the system. An intra-agent rule is applied to the agent itself. Fig. 1 shows a hybrid agent (agent A) with two neighbours (agents B and C) and where intra- and extra-agent rules are applied.

Extra-agent rules operate at the environment level outside the agent (extra-agent environment) while intra-agent rules are applied to the environment inside the agent. The hybrid agent may change based on intra-agent rules as a consequence of interactions with its neighbours, but is also capable of evolving in time without interaction with any external element. Fig. 2 presents some probable states of hybrid agent H consisting of two constituents, where the quantities of the agent's constituents change without any interaction with neighbours, thus illustrating the operation and expected consequences of the intra-agent rule. The change within the agent H is dictated by the intra-agent rule in the way that the quantity of one of the constituents can be replaced by any other one (Fig. 2(A)); consequently, the hybrid agent transforms to a single component agent with the same agent size which is equal to the sum of its constituents before transformation.

The quantity of both constituents can be decreased or increased (Fig. 2(B) and (C) respectively) which changes the agent size. The quantity of one constituent can be increased and other one decreased while the sum of quantities of the constituents in the agent may change (E) or may not change (D). When the size of the agent which might be determined by the sum of the quantities of its constituents is changed, the fractions of the quantities may be unchanged (same as Fig. 2(B)). Therefore,