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STUDENTS' CONCEPTIONS, TROUBLESOME KNOWLEDGE, AND THRESHOLD CONCEPT OF CATALYST EFFECT ON REACTION RATE

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ABSTRACT

Student conceptions provide valuable information for understanding learning difficulties and provide insight into how they can be addressed appropriately. Analyzing students' conceptions can also provide insight into what concepts are troublesome or serve as concepts affecting learning. Using the Interview About Event-Mental Model Diagnostic Test (TDM-IAE), twenty-one high school and university students' conceptions, troublesome knowledge, and threshold concepts for understanding the effect of catalyst to reaction rate were identified. Students mostly held partial mental models or mental models with misconceptions in which three concepts were considered troublesome and threshold concepts for understanding the effect of catalyst on reaction rate.

ABSTRAK

Konsepsi siswa memberikan informasi yang berharga untuk memahami kesulitan belajar dan memberikan wawasan bagaimana kesulitan tersebut dapat ditangani dengan tepat. Menganalisis konsepsi siswa juga dapat memberikan wawasan tentang konsep apa yang dianggap menyulitkan atau menjadi konsep yang mempengaruhi pembelajaran. Melalui *Interview About Event-Mental Model Diagnostic Test* (TDM-IAE), konsepsi dua puluh satu siswa sekolah menengah dan universitas, pengetahuan yang sulit, dan konsep ambang untuk memahami pengaruh katalis terhadap laju reaksi diidentifikasi. Siswa sebagian besar memiliki model mental parsial atau model mental dengan miskonsepsi dengan tiga konsep dianggap sulit dan konsep ambang untuk memahami efek katalis pada laju reaksi.

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INTRODUCTION

In understanding concepts, Perkins (1999) mentions knowledge that is likely to prove troublesome for learners and Meyer & Land (2003) define knowledge that is conceptually difficult for students to understand as troublesome knowledge. The basic idea of troublesome knowledge (Meyer & Land, 2003, 2005) is that in specific disciplines, there are "conceptual gateways" that lead to a previously inaccessible or perhaps troublesome way of thinking about something. Meyer & Land (2005) illustrate troublesome knowledge and threshold concepts with physiology as an example. In essence, when a medical student learns to propose a diagnosis and design a healing regime, understanding pain will aid diagnosis and healing because pain as threshold concept transforms medical students or clinical practitioners in thinking about a particular disease. In characterizing conceptual gateways, Meyer & Land (2005, pp. 373) suggested that conceptual gateways may be transformative (bring about a significant shift in the perception of a subject), irreversible (unlikely to be forgotten, or unlearned only through considerable effort), and integrative (exposing the previously hidden interrelatedness of something). In the same vein, a complete understanding of chemical concepts in chemistry is obtained by linking the three levels of chemical representation defined as macroscopic, submicroscopic, and symbolic levels for symbolic level cannot be separated from the macroscopic and submicroscopic levels (Ferreira & Lawrie, 2019; Berg, 2019).

Talanquer (2015) suggested that identifying threshold concepts for chemistry and characterizing how to master it will accommodate chemistry learning but studies concerning troublesome knowledge and threshold concept for chemistry are still very limited in the literature. Park & Light (2008), for example, explored that atomic structure is a potential threshold concept for study in science and particularly in areas such as spectroscopy and bonding theory. Loertscher et al. (2014) already identified threshold concepts for biochemistry, in which the study identified transition states, dynamics and regulation of biochemical pathways, basic physics of interactions, thermodynamics of macromolecular structure formation, and free energy as threshold concepts for biochemistry. Studies of troublesome knowledge and threshold concepts for other chemistry subjects are unfortunately rare. Therefore, identifying the nature and structure of the threshold of understanding and analyzing the troublesomeness of other chemistry concepts will offer valuable information for understanding student learning difficulties and provide insight into how they can be addressed.

Studies in chemistry education have shown evidence of students' difficulties in understanding reaction mechanisms. Bongers et al. (2020) study on university students unveiled that the students' answer to reaction mechanism questions was only moderately accurate, and their working mental model for picturing the reaction process reflected irresolute understanding of the reaction mechanism. In the same year, Watts et al. (2020) study of 543 university students' written descriptions of hydrolysis reactions showed that 26% of the students did not recognize the importance of reaction medium in reaction mechanism. The problems in understanding reaction mechanisms are not happening exclusively in higher education students. Earlier studies showed that students in secondary school (Cakmakci et al., 2006; Cakmakci, 2010) or high school students (Yalkincaya et al., 2012) equally struggle in understanding reaction mechanisms.

Reaction rate and the role of a catalyst are reaction mechanism features that are commonly misunderstood. Yalkincaya et al. (2012) study, for example, found that although students could define the reaction rate as the amount of substance consumed or produced in a particular timeframe, there were also students who overlooked the fact that the concentration of reactants cannot be constant during a reaction. Cakmakci's (2010) study also found that 49.03% of secondary and university students in the study held alternative conceptions about the effect of reactants concentration on the rate of a zero-order reaction, and 61.9% of students even faced difficulties in explaining how reaction rate changes as the reaction progress. The difficulties in fully understanding the rate of reaction and the role of a catalyst in a reaction were even found in preservice science teachers in which Cam et al. (2015) study found that although 54.3% of preservice science teachers can identify the catalyst in a reaction and 67.9% can identify factors affecting reaction rate, only 12.3% can give the correct response concerning the effect of catalyst on activation energy. Considering the supposed troublesomeness of the reaction rate concept and students' difficulty in understanding the role of catalyst in reaction mechanism, this paper identified troublesome knowledge, threshold concept, and students' conceptions of the catalyst effect on reaction rate to provide insight into student' learning difficulties and how they can be addressed.

METHOD

The study identified fourteen senior high school students (11th and 12th graders, seven students for each level) and seven first-year chemistry education students' conceptions, troublesome knowledge, and threshold concept of catalyst effect on reaction rate. A mental Model Diagnostic Test Interview About an Event (TDM-IAE) was used to probe students' conceptions. The TDM-IAE consisted of primary, general, and probing questions for two catalyst-reaction rate scenarios (homogenous and heterogenous catalyst). The two scenarios or *phenomena* were presented in the form of descriptions, pictures, and videos. After observing the phenomena, the students were given the main questions. Probing questions are asked if their answers are not optimal. Probing questions consisted of two general probing questions and special probing questions. Each student's interview was conducted through Zoom meetings in which the students freely determine the time of the interview. Interview time varies according to their speed and completeness in answering each question.

Each interview data (video recording and students' writing) was recorded, transcribed, and interpreted. The data obtained from interviews were analyzed to identify students' mental model profiles, analysis of conceptions, threshold concepts, and troublesome knowledge. The grouping of students' mental model profiles is based on students' understanding of the three levels of chemical representation and the linkages of these three levels (Wiji et al., 2021). The analysis of troublesome knowledge and threshold concepts was identified based on the characteristics of the troublesome knowledge and threshold concept (Meyer & Land, 2003; Hill, 2019; Wiji et al., 2021).

RESULTS AND DISCUSSION

Partially correct conception is characterized when a student's response provides a correct conception but still contains an irrelevant explanation. Students in this study, for example, were still unable to write down the reaction mechanism for the decomposition of hydrogen peroxide with a bromide ion catalyst and the reaction mechanism for adding ethylene with hydrogen using Ni catalyst. In addition, some students could not describe and explain the graph of the relationship between kinetic energy and molecular fractions, indicating that they could not connect submicroscopic and symbolic levels. This partially correct conception was found in each student's education category (11th grader, 12th grader, and 1st-year university students, Figure 1-3), suggesting that most students (62%) have a partial mental model about the effect of catalyst on reaction rate (Table 1). In the same vein, Yalcinkaya et al. (2012) study of 11th grade high school students found that 66% of students have a partial understanding of the effect of catalysts on reaction rate, in which this partial understanding includes specific alternative conceptions.

Table 1. Profile of Student Mental Model

Type	Characteristics	N (student)	Percentage
Complete mental model	a. Student's explanations for the main questions consist of three levels of representation. b. Student's explanations include three levels of representation after being guided by general questions and/or probing questions.	- -	0%
Partial mental model	The student's response provided the correct concept but there is an irrelevant explanation.	13 (S1, S2, S3, S8, S9, S11, S14, S15, S16, S17, S18, S19, S21)	62%
Mental model with misconception	The student's response provided a conceptual explanation but it was still a consistent explanation and was repeatedly wrong.	8 (S4, S5, S6, S7, S10, S12, S13, S20)	38%
Inconsistent mental model	Students do not provide feedback or provide irrelevant and inconsistent responses.	-	0%

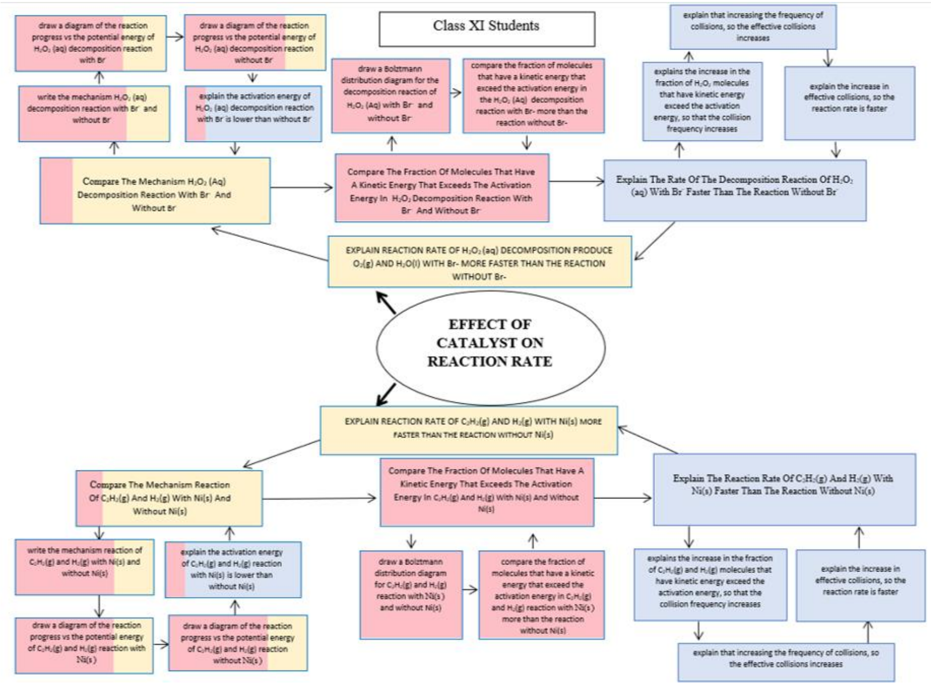

Figure 1. Mental Model Profile of 11th Grade Students. The color indicated correct (blue), partially correct (yellow) and wrong (red) answer.

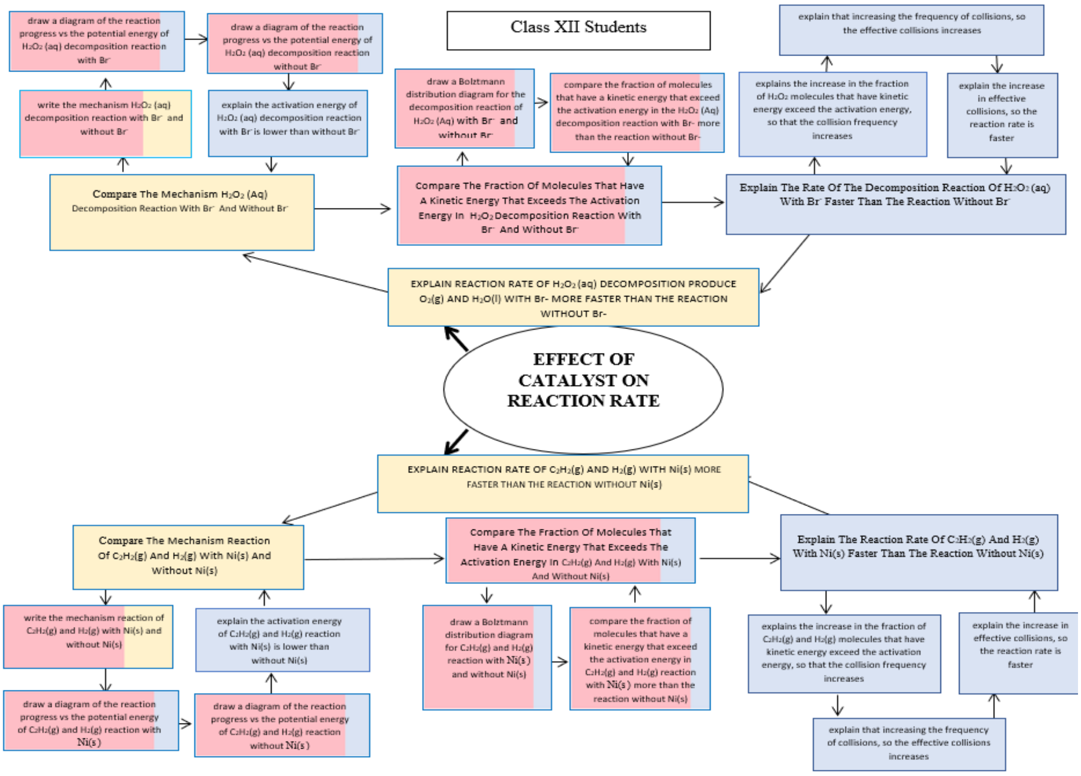

Figure 2. Mental Model Profile of 12th Grade Students

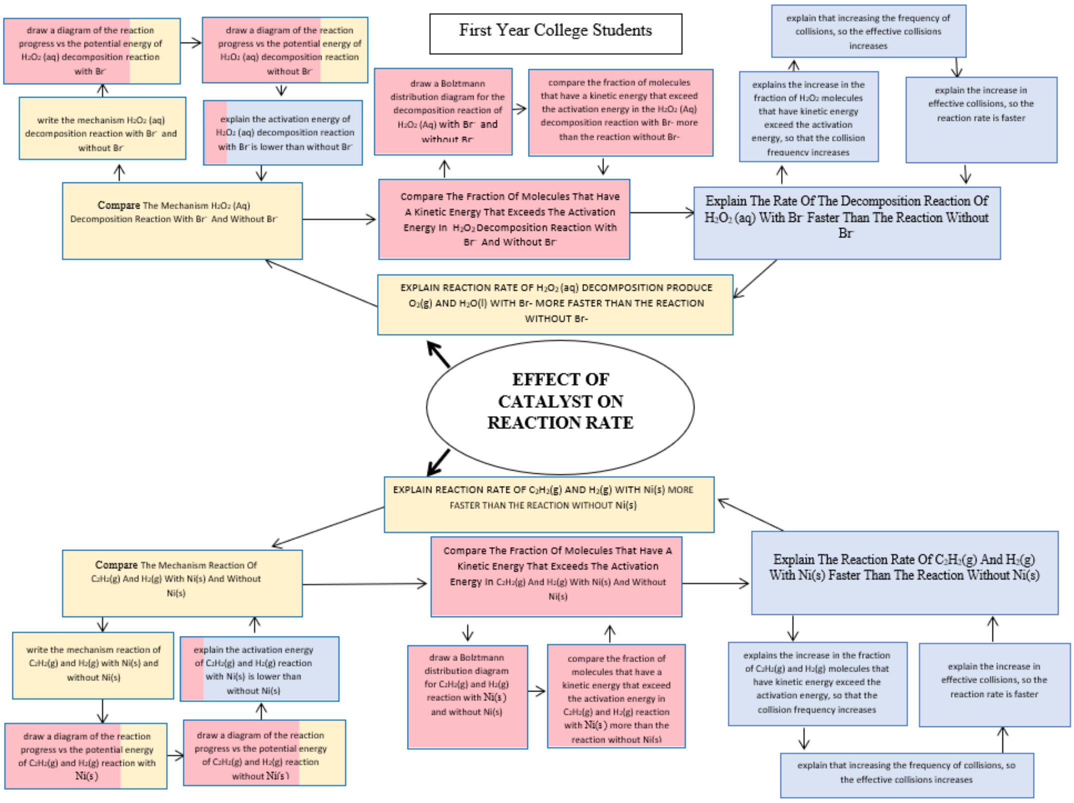

Figure 3. Mental Model Profile of First Year University Students

Table 2. Student Misconceptions About the Effect of Catalyst on Reaction Rate

No.	Misconception	Percentage
1.	Reaction with a catalyst can increase the activation energy and kinetic energy.	33,33%
2.	The reaction with the catalyst will produce more frequent effective collisions, so active energy increase.	4,76%
3.	The catalyst is not involved in the reaction.	14,3%
4.	The catalyst is not regenerated at the end of the reaction.	4,76%
5.	Heterogeneous catalysts are catalysts that are in liquid and solid phases, while homogeneous catalysts are catalysts that are in liquid and liquid phases.	4,76%

Table 3. Analysis of the Characteristics of Troublesome Knowledge

Concept	Concept Characteristics	Type of Troublesome Knowledge
Collision theory	Abstract, complex	Ritual knowledge
Activation energy	Complex, draw and explain graphics	Conceptually difficult
Kinetic energy	Complex, draw and explain graphics	Conceptually difficult

Table 4. Threshold Concept of the Effect of Catalyst on Reaction Rate

Threshold Concept Candidate	Characteristics		
	Troublesome	Integrative	Transformative
Collision theory	✓	✓	✓
Activation energy	✓	✓	✓
Kinetic energy	✓	✓	✓

Thirty-eight percent (38%) of students in our study provided conceptual explanations for two phenomena concerning the effect of catalysts on reaction rate but still had a consistent and repeatedly wrong explanation. S6, for example, believe that when a catalyst is involved in a reaction, it can increase the activation energy, and therefore, S6 consistently believe that catalysts are not involved in chemical reactions. These two misconceptions are the two types of misconceptions with the highest percentage of occurrence (Table 2). Yalcinkaya et al. (2012) also found similar misconceptions in which 24% of students in their study hold the alternative conceptions that a catalyst does not react with reactants or products. Similarly, Cakmakci (2010) identified that 39.6% of secondary and university students hold the misconceptions that catalyst does not affect or change the mechanisms of a chemical reaction.

Students in our study also have misconceptions about energy dynamics in a chemical reaction, as found in Lamichhane et al. (2018) study. They held alternative conceptions that reaction with a catalyst could increase activation and kinetic energy. However, as opposed to what our students believe, 14.3% of students in the Yalcinkaya et al. (2012) study believe that a catalyst decreases the kinetic energy of the molecules. The confusion around the connection between activation energy and the catalyst was also found in Cam et al. (2015) study, in which only 12.3% of preservice science teachers in their study can give correct responses concerning the effect of catalyst on activation energy. Yan & Subramaniam (2018) study further elucidated the confusion concerning catalyst and energy dynamics. These studies indicated that students have difficulty understanding energy profiles and might even confused lowering activation energy with lowering enthalpy change.

Collision theory (Le Vent, 2003) states that the number of successful collisions determines a chemical reaction. Brady et al. (2012) further elaborated that a catalyst accelerates the reaction rate in a chemical reaction by providing a new reaction mechanism with lower activation energy than the uncatalyzed reaction and increases the frequency of successful collision. The high percentage of students who hold alternative conceptions that a catalyst is not involved in a chemical reaction indicated that students still need help in understanding how the chemical reaction works or how catalysts promote the reaction rate. Therefore, collision theory which could explain the effect of a catalyst in a chemical reaction is the troublesome knowledge for understanding the effect of a catalyst on reaction rate. Similarly, the mechanism of activation and kinetic energy in a catalyst-induced chemical reaction that still creates confusion among students indicated that activation and kinetic energy could also be considered troublesome knowledge.

Perkins (1999) mentions that inert (passive knowledge), ritual (routine knowledge), conceptually difficult (knowledge that is hard to comprehend), and foreign knowledge (conflicting knowledge) are likely to prove troublesome for learners. In determining which concept falls into which type of knowledge, Hill (2019) summarizes and elaborates on what constitutes which type of knowledge (pp. 2). *Ritual knowledge* is characterized by following but not understanding a conceptual rule; *inert knowledge* is known but rarely used with no associated understanding; *conceptually difficult knowledge* involves several different pieces of information which may be counterintuitive, and lastly, *alien (foreign) knowledge* which goes against what you believe in. The three concepts -Collision Theory, activation energy, and kinetic energy- fall into a different type of troublesome knowledge (Table 3). Collision Theory, for example, is considereds as abstract and complex because students must systematically understand factors influencing a chemical reaction, the role of the catalyst in the reaction, and how these features are connected and construed in the Collision Theory. The complexity of the theory then makes the students may follow it but only understand it superficially: *the knowledge is merely ritual*.

In contrast to collision theory, understanding both activation and kinetic energy depends on student's ability to describe and explain energy graphs of the particles that react in the reaction without and with a catalyst. Moreover, students must also use several pieces of information to understand activation-kinetic energy dynamics in which the information might be counterintuitive, misinterpreted, or even supposedly interchanged with enthalpy change. Therefore, activation and kinetic energy can be considered as *conceptually difficult knowledge*.

Loertscher et al. (2014) and Hill (2019) stated that not all troublesome knowledge could be considered a threshold concept, that most but not all troublesome knowledge are threshold concepts for learning. Therefore, each concept proven to be troublesome in understanding the effect of catalyst on reaction rate must be analyzed based on threshold concept criteria, namely troublesome, transformative, and integrative (Meyer & Land, 2003; Loertscher et al., 2014; Hill, 2019). Data from students' interviews showed that collision theory, activation, and kinetic energy already fulfilled the troublesome criteria, and, therefore, transformative integrative characteristics were eventually addressed.

A concept fulfilled transformative characteristics if the concept brings about a significant shift in the perception of a subject (Meyer & Land, 2003) or what Loertscher et al. (2014) determine by contemplating what subject or ideas are unlocked once the concept is understood. We addressed the characteristics by analyzing students with the most complete and correct answers for each education level. As previously mentioned, the students only arrived at the partial mental model and no students held a complete mental model. However, out of the students who held partial mental models, S8 understood almost all catalyst effects on the reaction rate phenomena. S8, for example, almost fully understands the phenomena in which S8's ability to understand activation and kinetic energy enables S8 to explain the collision theory confidently. Conversely, S2 and S15 did not understand factors influencing chemical reaction, the energy dynamics in the reaction, and how these features are connected and construed in the collision theory. This eventually made them unable to correctly explain the effect of a catalyst on the rate of a reaction. Thus, all three troublesome knowledge also fulfilled the *transformative* criteria.

The last criteria of the threshold concept are integrative, or what Meyer & Land (2005) identified as a concept exposing the previously hidden interrelatedness of something. S2 explained that the presence of a catalyst can lower activation energy and increase kinetic energy. This misconception shows that students need help in distinguishing or understanding the dynamics of activation and kinetic energy, which unfortunately also led to their inability to explain collision theory and the effect of catalysts on reaction rate. S8's answers showed that S8 could distinguish between activation and kinetic energy, which led S8 to explain collision theory correctly and, thus, correctly explain the catalyst effect on reaction rate. This indicated that to understand the effect of catalysts on reaction rate; students must understand the concept of activation energy, kinetic energy, and collision theory because the concepts are interrelated or *integrative*. Consequently, although Loertscher et al. (2014) and Hill (2019) stated that not all troublesome knowledge could be considered as threshold concepts, all three troublesome knowledge for understanding the effect of catalysts on reaction rate also served as threshold concepts (Table 4).

Loertscher et al. (2014) emphasize that identifying threshold concepts is only meaningful if it used to make effective changes in teaching and learning. They pointed out that next critical step is producing instruction and making changes that support learning threshold concepts. Studies have investigated the effect of instructional changes in chemical reaction teaching and learning. Calik et al. (2010) employed conceptual change pedagogy to improve students' conceptions of reaction rate, and the study reported that the teaching intervention helps the students overcome alternative conceptions of reaction rate concept. In their study, the approach proved successful because misconceptions concerning the effect of catalysts on reaction rate were reduced by more than 50%. Further, Tastan Kirik & Boz (2012) also implemented cooperative learning and animation for teaching chemical kinetics. After the intervention, misconceptions concerning the effect of catalysts in chemical reactions were significantly reduced. Therefore, designing and implementing instructtional approaches specifically designed to improve students' conceptions by also considering the role of troublesome knowledge and threshold concepts can be explored in future studies.

CONCLUSION

Most students have partial mental models and mental models with misconceptions, characterized by common thinking faultiness in understanding the effect of catalyst on reaction rate. Collision theory, activation energy, and kinetic energy are troublesome and threshold concepts for students to correctly understand the effect of catalysts on reaction rates. To improve students' conceptions of the effect of catalyst on reaction rate, instructional approaches should also consider the role of troublesome knowledge and threshold concepts for learning reaction mechanism.

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