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Simplified Model for Data Collection of Liquid Products in Process Manufacturing

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Abstract: In the realm of process manufacturing, tracking product flow and data alignment remains important. Current technologies primarily cater to discrete and batch processing, leaving a gap in continuous process tracking. This paper introduces a simplified model designed to calculate the transit time slots as products traverse specific system passages, considering systems characterized by pipeline branching and mixing tanks. The model presented herein is based on certain idealized conditions and has not yet been empirically validated. Nevertheless, it provides a method for the calculation and allocation of comprehensive data histories of arbitrarily defined product units within continuous process manufacturing systems. It holds potential for future extension and refinement.

Keywords: data allocation, product tracking, process manufacturing, CSTR

1 Introduction

To optimize manufacturing processes across multiple process steps, the collection and integration of the data generated in each process step with respect to the product units is necessary. A product unit at the end of a production line is a result of all the process steps that it went through. Its quality characteristics are often related to multiple process steps whose parameters and behaviors are inter-related. Therefore, analyzing and optimizing product quality as well as production processes require product-oriented data integration across multiple process steps.

Existing methods enable product-oriented data integration through assigning product units with unique IDs at early process steps [Di19]. Such methods mainly focus on discrete manufacturing or batch manufacturing. In contrast, product-oriented data allocation in continuous manufacturing is less discussed, especially when handling e.g., liquid or

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gaseous materials. Hereby, one of the challenges is to track back the past positions of a product unit along the material flows in the production plant [TMK21].

Continuous Stirred Tank Reactors (CSTR) are widely used in continuous manufacturing as well as for representing the behavior of sections in continuous process which provide a product holdup. The residence time distribution (RTD) is often used to characterize the mixing dynamics inside the CSTR [RK08] and to trace disturbances introduced during operation [Kr18]. The past (i.e., historical) position of a product unit along the process route is not yet well studied. However, e.g., in the food and beverage industry or glass container manufacturing, data is collected and used for process monitoring and optimization [SKS23], supporting production planning and performance analysis [CV20] or inspecting defects [Li19], without considering the historical position of a given product unit in the production lines. This, however, becomes necessary, if historical time intervals of sensor and actuator signals along the production route of a plant shall be allocated to a specified product unit at the plant outlet, e.g., for reasons of product data collection or quality investigations.

In the tracking of discrete products, each product unit is typically conceptualized as a point. Its position can be calculated and tracked by measuring the distance between the product unit and some reference points (e.g. using tags and anchors [Sl19]). This is feasible, since a certain type of product usually has a regular size. Methods for tracking disturbances in continuous manufacturing [Kr18], however, cannot be used to calculate the transit time of a defined product unit passing by the passages (at certain places) in the whole process. Therefore, for comprehensive allocation of information pertaining to product fractions, a flexible method is required for localizing a variably definable quantity of product units.

To allocate the existing data more precisely to a given product unit, it is necessary to provide more accurate information about the relation of position and transit time of the considered product unit within the production process. This work introduces a simplified model that enables locating the start and the end of any liquid product units in continuous production processes, such that the relevant machine data time interval can be allocated to the corresponding product unit as the relevant product data generated during the product's production.

This article is structured as follows: Section 2 introduces on the important assumptions and required information for the calculation, providing the basics of the model used for data allocation in process manufacturing. Section 3 delves into the theoretical foundations of the model and the handling of CSTR within this paper.

Section 4 presents the methodologies for data allocation involving pipeline branching and the handling of CSTRs, showcasing the application and flexibility of the model. Section 5 discusses the limitations and challenges of the current model, proposing areas for future improvement and research.

2 Assumptions and required information

This section introduces and explains the assumptions underlying the model used in this work, which are applicable under ideal conditions. The scope of the paper focuses on developing a method to track and analyze the positions of liquid product units within pipes and tanks. Specifically, the paper aims to calculate transit time slots for a given product unit based on sensor or actuator position, sensor or actuator time-series data, and process events. This includes the calculation of the transit time slots for when a product unit passes a specific point in the system, such as a sensor, actuator, pipe branching etc. This paper also endeavors to address the complexities involved in product tracking and data allocation in continuous processes with branched pathways.

2.1 Assumptions

To facilitate the computation of historical product positions, the model designed in this work assumes that the behavior of the liquid product conforms to a plug flow regime. This assumption simplifies computational complexity by treating the flow of the liquid through the system as uniformly moving at the same velocity at a given point in the plant, without back mixing or variations in velocity across different sections of the conduit. The other complex fluid behavior is not considered in this work, such as the fluid behavior at connections or junctions.

In the production plant, the cross-sectional area at a given position is utilized to represent the smallest unit of the product. The midpoint of this cross-section serves as the computational location for determining the product's position within the system.

The direction of liquid flow is considered the positive direction for product positioning, aligning the movement of the product within the plant’s flow dynamics. The trajectory of the product movement is represented by a line connecting the midpoints of the process equipment through which the product flows.

The model also assumes that the process equipment within the system is always fully saturated with the product, ensuring that there are no partial fills that might alter the flow dynamics. Additionally, it neglects the impact of height variations in the piping on the flow rate, assuming that gravitational effects and potential energy changes are minimal.

These assumptions streamline the calculation model by eliminating the need to account for complex fluid dynamics associated with varying fill levels and elevation changes, thereby focusing solely on the flow behavior under consistent and controlled conditions.

2.2 Required information

Besides the assumptions, some data are required to calculate the product position and allocate the data to the selected product unit. These parameters should be either readily accessible or ascertainable through computation or measurement. They are categorized into three groups.

Static Data:

Geometry of Process Equipment: Knowing the exact dimensions and configurations is crucial. This includes diameters, lengths, curvature, and the layout of piping systems, as well as the shape and volume capacities of tanks.

Technical Specifications of Sensors and Actuators and Their Connections: Detailed information about the sensors and actuators involved in the system, such as their type, range, accuracy, and location, is necessary. This ensures that data collected is relevant and precise for the system's needs.

Dynamic Data:

Events During Processes: This includes changes in the flow paths, such as valve operations (open/close), shifts in direction of flow, and other process adjustments that impact the movement and position of the product.

Product Properties:

Flow Rates (Volume/Mass): Real-time data on how much product is moving through piping the system.

Density: Measurements or calculations of the product's density, which can affect flow dynamics and require adjustments in process handling.

3 Simplified model for calculating the position of liquid

To compute the transit time slot corresponding to a product unit passing through a predetermined location, it is necessary to determine the temporal markers denoting the beginning and the end of the observed product unit. Consequently, one must calculate the moment when a cross-section of the product traverses the location. This involves establishing a relationship between the known flow properties, the geometric configuration of the process system, and the temporal progression of the product within it.

3.1 Method to calculate the position of a product's cross-section

The relationship described above involves two cross-sections within a process system, specifically between an outlet at position x_a and another given position x_R (see Fig. 1 (a)).

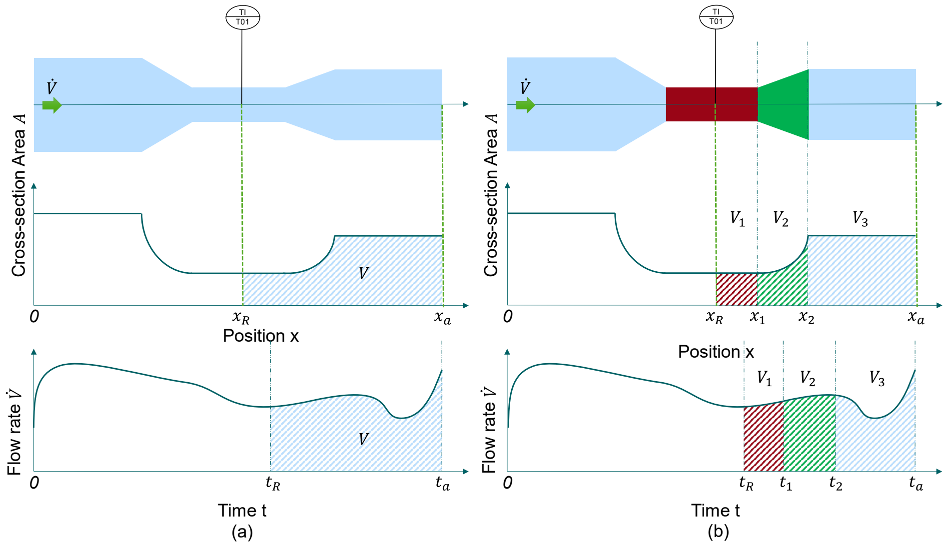

Fig. 1: (a) Theoretical foundation of calculating product position. (b) Calculation in segments.

The volume between the two cross-sections from x_R to x_a can be mathematically expressed as the integral of the cross-sectional area $A(x)$ with the positional difference between x_R and x_a. This is mathematically noted as: $V = \int_{x_R}^{x_a} A(x) \cdot dx$, where V represents the volume between the two cross-sections, $A(x)$ is the cross-sectional area, and dx is the infinitesimal segment of the path between x_R and x_a.

Furthermore, this volume can also be equated to the integral of the product flow rate $\dot{V}(t)$ over the time difference between t_R and t_a, which corresponds to the times when the product passes through x_R and x_a respectively: $V = \int_{t_R}^{t_a} \dot{V}(t) \cdot dt$, where $\dot{V}(t)$ is the time-variable flow rate of the product at the cross-section, t_R and t_a are the respective times at which the product is at positions x_R and x_a[7]. We can deduce the following Equation (1):

$$\int_{x_R}^{x_a} A(x) \cdot \mathrm{d}x = \int_{t_R}^{t_a} \dot{V}(t) \cdot \mathrm{d}t \tag{1}$$

Based on the previously stated assumptions, the sole unknown variable t_R within the Equation (1) can be resolved mathematically.

In practical computation, it is not always feasible to calculate the volume of each process equipment by simple integration due to the complexity of certain geometries. Hence, the

[7] Here is constant density and incompressible fluid considered.

target region may be subdivided into several contiguous segments, (see Fig. 1 (b)), with the volume of each segment calculated individually.

Based on the segmentation $V = V_1 + V_2 + V_3$ in Fig. 1 (b), the Equation (2) can be derived:

$$\int_{x_R}^{x_a} A(x) \cdot \mathrm{d}x = \int_{x_R}^{x_1} A(x) \cdot \mathrm{d}x + \int_{x_1}^{x_2} A(x) \cdot \mathrm{d}x + \int_{x_2}^{x_a} A(x) \cdot \mathrm{d}x \tag{2}$$

Equation (1), which provides the theoretical foundation for the model discussed in this work, does not mandate the use of integration for practical computations. This is practical for process equipment that is resistant to straightforward volumetric integration, wherein the entire part's volume and its length along the product path may be employed directly in the analysis. When the target location does not reside within a process equipment of complex geometry, it is advisable to employ the holistic approach for the computation of its volume. For process equipment with simple geometric shapes, such as straight pipelines, it is preferable to employ proportional calculations rather than integration methods when determining the required volume inside the equipment.

The following relationship can be derived by combining Equation (1) and Equation (2):

$$\int_{t_R}^{t_a} \dot{V}(t) \cdot \mathrm{d}t = \int_{t_R}^{t_1} \dot{V}(t) \cdot \mathrm{d}t + \int_{t_1}^{t_2} \dot{V}(t) \cdot \mathrm{d}t + \int_{t_2}^{t_a} \dot{V}(t) \cdot \mathrm{d}t \tag{3}$$

The variable t_R within the Equation (3) can be resolved step by step in a backward sequence:

$$t_R \leftarrow t_1 \leftarrow t_2 \leftarrow t_a \tag{4}$$

The Equation (4) also serves as the foundation for calculating when paths branch within the piping structure. It provides the necessary mathematical framework to assess how variables change at junctures where the flow diverges.

3.2 Handling of mixing time in CSTR

In an ideal CSTR, the assumption is that the mixing is instantaneous and complete. But in practice, the time it takes for the contents to be well mixed varies depending on the specific conditions and setup of the reactor. Generally, the mixing time in a practical CSTR can range from a few seconds to several minutes or more.

One simple empirical method for estimating mixing time θ_m is given by Equation (5):

$$\theta_m = \frac{\mathrm{K}}{N} \tag{5}$$

where N is the impeller rotational speed and K is a constant that depends on the type of impeller and the reactor geometry [Ag15]. The constant K can vary depending on the specific setup and is often determined from experimental data or from literature if similar systems have been studied.

4 Data allocation with a combination of different process equipment

This section illustrates the methodology for calculating the flow of product streams through a complex piping system with a theoretical example. Using the method in Section 3, we model the transit times and volumes for each stream. By applying this approach to each segment, we demonstrate how to trace the path and position of multiple converging streams through a network of interconnected process equipment in a complex piping system.

4.1 Calculation with pipeline branching

The observed product at the outlet may comprise streams that have traversed distinct pathways, as indicated by the green and red routes in Fig. 2 (a). These streams do not consistently pass through the same passage and may spend varying durations within the production system. For instance, the green stream in Fig. 2 (a) follows a trajectory passing the positions of the sensors T01, T02, and T04, whereas the red stream passes along the positions of the sensors T01, T03, and T04. Depending on the flow rate and the geometry of the process equipment in both routes, those two product streams may have passed by T01 at different times. To accurately assign machine data to the respective product streams, it is essential to determine the precise moments when these streams passed specific passages, requiring the calculation of transit time and tracing of their historical positions throughout the production process.

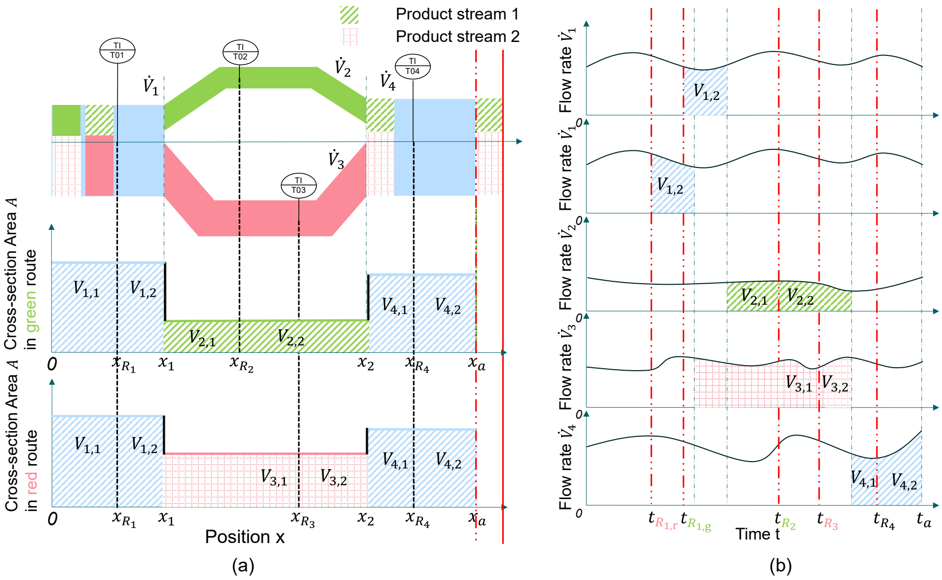

Fig. 2: (a) Product streams in a system with pipeline branching. (b) Results of the calculation

To calculate the transit time at which a product passes through a given passage within a particular route, it is necessary to address the separation of the product into different streams at the branching points. The paper employs Equation (3) at the junctures of process equipment to handle the separation of product flow, treating the product as two distinct portions pre- and post-branching. When the product is separated into multiple streams, the respective times for the different streams within their individual routes are calculated separately at the position where the streams diverge (e.g. at x_1 and x_2).

For instance, to calculate the transit time at which the product passes sensor T02, the time it takes for the product to reach position x_2 must be first determined using the flow rate $\dot{V}_4$ and the volume V_4. Given the previously stated assumptions, x_a, t_a, $\dot{V}_4$, $\dot{V}_2$, and x_{R_2} are known. Since the geometry of all the process equipment in the system is also known, the volume $V_{2,2}$ (and $V_{2,1}$) can be also determined. Subsequently, the flow rate $\dot{V}_2$ and the volume $V_{2,2}$ are used to compute the time t_{R_2}, at which the product reaches the sensor at x_{R_2} (s. Fig. 2 (b)).

The t_{R_3} can be determined similarly. In the example provided within this paper, the times at which the two streams pass sensor T01 may differ. This is due to the difference in the time taken for them to reach position x_1 along the two routes, resulting in different passage times at T01 (s. Fig. 2 (b)), denoted as $t_{R_{1,\mathrm{r}}}$ (in red route) and $t_{R_{1,\mathrm{g}}}$ (in green route). The times $t_{R_{1,\mathrm{r}}}$ and $t_{R_{1,\mathrm{g}}}$ represent the moments when the end (the latter flowing part) of the product reaches sensor T01. The data measured by T01 is associated with these times (s. Fig. 3 (a)). To assign a time window that correlates with a considered unit (i.e. volume) of the product at the outlet of the process, the time when the first outflowing part of the product (indicated by the solid line in the diagram in Fig. 2 (a)) arrives at T01.

The part between the solid and dashed lines (s. Fig. 3 (b)) corresponds to the time window during which the observed product passes sensor T01.

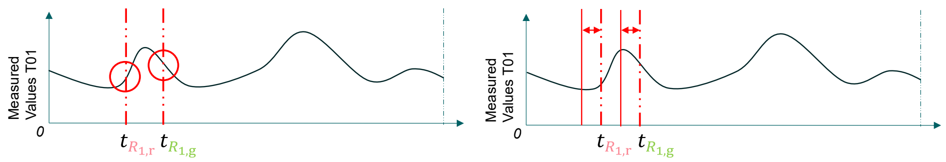

Fig. 3: (a) Data allocation for a product's cross-section. (b) Data allocation for the observed product.

4.2 Calculation with CSTR

In the context of a Continuous Stirred Tank Reactor (CSTR), the plug flow model is not applicable due to the inherent mixing dynamics within the reactor. Products in a CSTR are homogeneously mixed over a period, leading to a scenario where the composition of the product exiting the reactor is essentially identical to that of the product entering. Given this situation, for the purposes of assigning product-related data with observed products, the paper treats the reactor in the following manner:

Regardless of the volume of the CSTR, once the designated mixing time has elapsed, it is assumed that the product at the inlet has effectively reached the outlet, where it, though, has the composition like in the CSTR, which, however, is not relevant for the transit time calculation that we address in this paper.

As shown in Fig. 4 (a), the system example includes several CSTRs (numbered with 1 to 3), which are assumed not to affect the overall length of the remaining parts of the pipeline in this paper. When calculating the transit time a product passes through a specified passage, it is essential to account for the mixing time associated with each CSTR based on its relative position to the passage.

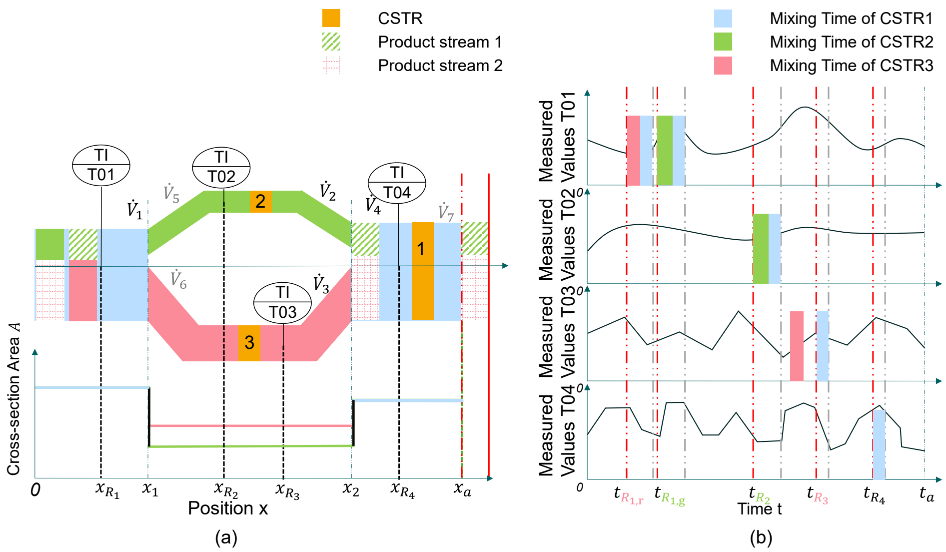

Fig. 4: Product streams in a system with pipeline branching and CSTR. (b) Results of the calculation.

As depicted in Fig. 4 (b), the presence of a CSTR introduces a delay in the timeline of calculations as compared to scenarios without a CSTR. Consequently, the transit time at which a product's cross-section passes through a passage is shifted from the position indicated by the grey dashed line to that marked by the red dashed line. For instance, sensors T01 and T02 are influenced by the delay induced by two CSTRs, while T03 and T04 are affected by only one CSTR. The method to calculate the transit time slot remains the same.

5 Discussion

This model provides a method to calculate and allocate the whole data history of product units with arbitrary defined quantities of product in continuous process manufacturing. Since this model is simplified and designed under several ideal conditions, it should be validated using either a practical system or simulation. The model can and should be extended to cover, e.g., parameter uncertainties and to allow for online applications.

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