# A *FRIDAY 13$^{TH}$* RISK MODEL FOR FAILURE IN CROSS – FLOW MEMBRANE FILTRATION OF PASSION FRUIT JUICE


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## ABSTRACT

Membrane filtration for clarification is a widespread unit-operation in the beverage industries. Unexpected membrane fouling (failure) can significantly reduce clarification efficiency. A *Friday 13$^{th}$* (*Fr 13*) risk model for membrane failure is developed and illustrated with independent data for yellow passion fruit juice (*Passiflora edulis var. flavicarpa*) and a comparison made with a traditional evaluation. The aim was to gain insight into the risk of stochastic impact on failure in a well-operated cross-flow membrane plant used in juice clarification. A risk factor ($p$) is defined in terms of the design permeate ($J'$) and actual critical ($J_{critical}$), flux. A refined Monte Carlo sampling of transmembrane pressure ($\Delta P$) and filtration time ($t$) is used to simulate membrane behavior. Results reveal that some 7 % of all filtrations will fail to achieve $J_{critical}$ with a practical tolerance and typical commercial conditions over an extended period. This insight is not available from traditional evaluation.



Keywords: membrane fouling, juice clarification, unexpected membrane failure, *Friday 13$^{th}$* risk modelling


## 1. INTRODUCTION

Yellow passion fruit (*Passiflora edulis var. flavicarpa*) is a tropical fruit which is widely used as an ingredient in formulated beverages and fruit products. However, traditional filtration methods such as distillation, adsorption and pasteurization, lead to a loss of nutritional and aromatic compounds (Domingues, Ramos, Cardoso and Reis 2014). Recently, non-thermal membrane cross-flow processing is becoming a widely substituted separating technology in juice clarification, because it provides high sensorial quality products with less loss, manpower and reduced processing time and operational costs over traditional methods (D' souza and Mawson 2005).

However, fouling is a key limitation in cross-flow membrane processing. The transient accumulation of rejected materials at the interface of the membrane can result in a reduced permeate flux or partial blockage. In juice clarification, a low permeate flux can substantially reduce process efficiency and product (juice) safety (Cassano, Marchio and Drioli 2006).

We are interested in the notion that no matter how good the design and operation of plant, there will be an unexpected, occasional and sudden (surprise) failure. Davey and co-workers have titled this practical phenomenon *Friday 13$^{th}$* syndrome (*Fr 13*) to explain the nature of the event (e.g. Davey, Chandrakash and O'Neill 2013; Davey 2010). Their hypothesis is that: *random variation in plant parameters can accumulate in one direction and leverage significant change in plant or product*. These unexpected failures can be mistakenly blamed on 'human error' or 'faulty fittings' (Davey and Cerf 2003; Davey 2010). According to the recent *Blackett Review* (Anon. 2011) 'high-impact', low-probability' failures are an emerging and practical challenge for various operations of a range of scale (Anon. 2011).

Although several mathematical models for juice filtration have been reported (Nandi, Das and Uppaluri 2012; Razi, Aroujalian and Fathizadeh 2012; Cassano, Marchio and Drioli 2006; Cui, Jiang and Field 2010) there is however no model to meaningfully assess risk of fouling (failure). Further, these do not involve the impact of a stochastic affects.

### 1.1. This study

Against this background we undertook research into synthesis and simulation of a novel *Fr 13* model for vulnerability to stochastic failure of widely used cross-flow membrane filtration plant. The model is illustrated using independent data of Domingues, Ramos, Cardoso and Reis (2014) for yellow passion fruit (*Passiflora edulis var. flavicarpa*) juice. A comparison is made with a traditional evaluation.

A *Fr 13* risk model is based on the underlying unit-operations model together with a clear definition of failure and refined Monte Carlo (r-MC) (*Latin Hypercube*) sampling (Zou and Davey 2014; Davey, Chandrakash and O'Neill 2013; Davey 2011).

The aim was to gain new insight that can be used to improve design of operations with reduced vulnerability to failure, together with improved process efficiency (and safety).

## 2. MATERIALS AND METHODS

### 2.1. Synthesis of a Unit-operations Model for Cross-flow Membrane Filtration

An acceptable unit-operations model for a well-operated cross-flow membrane process necessitates integration and synthesis of equations for transmembrane pressure ($\Delta P$), filtration time ($t$), membrane surface area ($A$), kinetic model constant for a particular juice ($K_c$) and an adjust parameter ($n$) according to one of four fouling modes (Domingues, Ramos, Cardoso and Reis 2014; Field, Wu, Howell and Gupta 1995 ).

Based on the model recently synthesized by Zou and Davey (2014) and, Bowen, Calvo and Hernandez (1995) and Field, Wu, Howell and Gupta (1995), we can write (all symbol used are carefully defined in the Nomenclature) for the design permeate flux ($J'$):

$$' = J_0 \cdot \left[1 + K_c \cdot J_0^{(2-n)} \cdot t\right]^{1/(n-2)} \qquad (1)$$

$J_0$ is obtained from initial membrane performance testing with deionized (clean) water (Domingues, Ramos, Cardoso and Reis 2014).

The parameter $n$ is fixed based on the principal fouling modes of the cross-flow membrane process: $n$ = 2 for complete pore blocking; $n$ = 1.5 for internal pore blocking; $n$ = 1 for partial pore blocking; and, $n$ = 0 for cake filtration layer. Many researchers (e.g. Domingues, Ramos, Cardoso and Reis 2014; Nandi, Das and Uppaluri 2012; Razi, Aroujalian and Fathizadeh 2012; Cassano, Marchio and Drioli 2006; Cui, Jiang and Field 2010) have reported cake filtration with $n$ = 0 is the major mode to describe fouling mechanism with juice processing, including passion fruit, apple, pineapple, mosambi and orange juices.

The permeate flux of the deionized water ($J_0$) is important to obtain the membrane capacity and is defined as (Schafer, Andritsos, Karabelas, Hoek, Schneider and Nystrom 2005):

$$_0 = \frac{\mu_T}{\mu_{T_{20°C}}} \cdot \frac{Q}{A \cdot \Delta P} \qquad (2)$$

where Q = clean water flow rate at the treating temperature, and $\mu_T$ and $\mu_{20^{O}C}$ are, respectively, the viscosity of clean water at operation, and a reference 20 $^{O}$C (Roorda and Graaf 2001). Substitution for $J_0$ from Eq. (2) and $n$ = 0 into Eq. (1) and simplifying gives:

$$' = \frac{\mu_T}{\mu_{T_{20°C}}} \cdot \frac{Q}{A \cdot \Delta P} \cdot \left[1 + K_c \cdot \left(\frac{\mu_T}{\mu_{T_{20°C}}} \cdot \frac{Q}{A \cdot \Delta P}\right)^2 \cdot t\right]^{-0.5} \qquad (3)$$

### 2.2. Critical Permeate Flux for Passion Fruit Juice

During cross-flow membrane filtration, there exists a flux below which a decay of flux with time does not occur; above this flux fouling is observed (Field, Wu, Howell and Gupta 1995). This flux is called the critical flux ($J_{critical}$) which is the design, or operation, level for successful membrane filtration without fouling.

Practical experimental data for cross-flow membrane filtration of passion fruit (*Passiflora edulis var. flavicarpa*) juice have been independently reported by Domingues, Ramos, Cardoso and Reis (2014) at a processing temperature of 25 $^{O}$C. Hollow fibre membranes with an average pore diameter of 0.40 µm and surface area of 0.056 m$^2$ together with $\Delta P$ = 100 kPa and 5.4 x 10$^{-6}$ m$^3$ m$^{-2}$ s$^{-1}$ < $J$ < 2.78 x 10$^{-6}$ m$^3$ m$^{-2}$ s$^{-1}$ were used. These data are conveniently re-plotted as Figure 1.

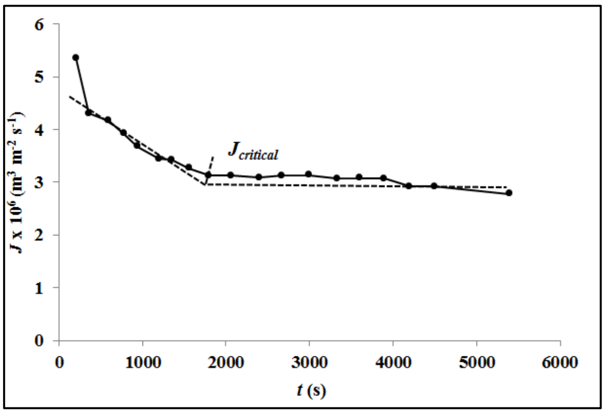


Figure 1: Experimental data for permeate flux (n = 19) in cross-flow membrane filtration of passion fruit juice (*Passiflora edulis var. flavicarpa*) at $\Delta P$ = 100 kPa (adapted from Domingues, Ramos, Cardoso and Reis 2014)

From Figure 1, the critical flux, $J_{critical}$ = 3.125 x 10$^{-6}$ m$^3$ m$^{-2}$ s$^{-1}$. This is determined by the intersection of lines tangent to the initial (0-1600, s) and terminal (3300-5400, s) parts of the curve, as shown on the figure. It is seen in the figure that $J_{critical}$ for the passion fruit juice will occur at $t$ = 1800 s.

All $J'$ < $J_{critical}$ indicates membrane fouling (failure). Cleaning or replacement of the membrane is then needed.

The unit-operations model for cross-flow membrane filtration of passion fruit juice is defined by Eq. (1) through (3), together with the value of the critical permeate flux ($J_{critical}$).

### 2.3. Traditional Single Value Assessment Solution

The traditional method for solution of a unit-operations model is called the 'estimated value' or 'single value assessment' (SVA) (Sinnott 2005; Davey 2011).

For typical commercial filtration of passion fruit juice, initial operating conditions include $\Delta P$ = 100 kPa; $\mu_T$ = 0.812 x 10$^6$ pa s; $\mu_{20^{0}C}$ = 1.002 x 10$^6$ pa s; $Q$ = 1.8 x 10$^{-3}$ m$^3$ s$^{-1}$; $A$ = 0.056 m$^2$; $K_c$ = 5.6 x 10$^7$ s m$^{-2}$ and $t$ = 1800 s (Domingues, Ramos, Cardoso and Reis 2014).

Substitution into Eq. (3), gives the SVA value for the permeate flux, $J'$ = 3.149 x 10$^{-6}$ m$^3$ m$^{-2}$ s$^{-1}$.

## 2.4. Defining Failure Risk

A risk factor ($p$) for vulnerability to failure of the cross-flow membrane can be conveniently defined together with a practical tolerance (Zou and Davey 2014; Davey, Chandrakash and O'Neill 2013) such that:

$$p = -\%tolerance + 100\,(\frac{J'}{J_{critical}} - 1) \quad (4)$$

where $J'$ is the instantaneous value of the permeate flux (or more strictly one membrane operation scenario). For an assumed practical tolerance of 2 % (Davey, Chandrakash and O'Neill 2013), Eq. (4) gives:

$$p = -2 + 100\,(\frac{J'}{J_{critical}} - 1) \quad (5)$$

That is, if the value of permeate flux is less than 1.02 times the critical flux, the filtration has failed.

The risk factor equations are computationally convenient because at all $J' < J_{critical}$, $p > 0$.

The novel *Fr 13* model for the cross-flow filtration of passion fruit juice is defined by Eq. (1) through (5), together with the experimentally determined value of $J_{critical}$.

## 2.5. *Fr 13* Simulations of Cross-flow Membrane Filtration of Passion Fruit Juice

In *Fr 13* the key plant parameters are defined not by a single (best) estimate as with the traditional SVA but by a probability distribution of values, the mean of which generally agrees with the SVA (e. g. Davey, Chandrakash and O'Neill 2013; Zou and Davey 2014; Patil, Davey and Daughtry 2005).

A r-MC sampling, *Latin Hypercube*, is used to ensure sampling covers the entire range of the input distributions (*see* Vose 2008, Davey, Chandrakash and O'Neill 2013 and Davey 2011 for a detailed explanation). To guarantee the output distribution is *Normal*, a minimum number of samples is needed, this is usually 1,000 to 50,000 (Davey K R – unpublished data). (It is generally a simple matter to visually establish this however by inspection of the output distribution).

In the absence of specific data, it is assumed that during cross-flow filtration the practical variation about the operational mean value of both transmembrane pressure ($\Delta P$) and filtration time ($t$) will be a standard deviation (stdev) = 2 %. An appropriate probability distribution for practical values of $\Delta P$ and $t$ are therefore: **RiskNormal** (mean, stdev, **RiskTruncate** (minimum = mean – 2 x stdev), (maximum = mean + 2 x stdev)) (Davey, Chandrakash and O'Neill 2013; Davey 2011). A desired consequence of the 2 x stdev about the mean to obtain the minimum and maximum is that nearly all values (95.45 %) fall in this interval (Sullivan 2004).

For this study, the transmembrane pressure becomes: $\Delta P$ = **RiskNormal** (100, 2, **RiskTruncate** (96, 104)), and; filtration time: $t$ = **RiskNormal** (1800, 36, **RiskTruncate** (1728, 1872)). It is seen that each distribution has been truncated to limit the range to values that can practically occur (Domingues, Ramos, Cardoso and Reis 2014; Davey, Chandrakash and O'Neill 2013).

The *Fr 13* simulations for the cross-flow membrane were performed in Microsoft Excel™ together with a commercial add-on *@Risk* (pronounced *at risk*) version 5.5 (Palisade Corporation). Because spread sheeting tools are used widely this means results can be communicated readily to a range of users of varying sophistication. All values $p > 0$ indicate a failure of passion fruit cross-flow filtration.

## 3. RESULTS

Table 1 presents a summary comparison of results from the traditional SVA and new *Fr 13* model for cross-flow membrane filtration of passion fruit juice. The membrane parameters are given in column 1 of the table. The traditional SVA is shown in column 2. Computations can be readily read down this column.

For the *Fr 13* model 50,000 r-MC samples of $\Delta P$ and $t$ were simulated. This provided a sufficiently *Normal* output distribution (Figure 2).

Column 3 of Table 1 shows one only of the 50,000 filtration scenarios. It can be observed that at $\Delta P$ = 98.77 kPa and corresponding $t$ = 1748.78 s, the value of risk factor, $p$ = 0.0851 (> 0), indicating a membrane failure.

The 50,000 process scenarios are conveniently summarized as Figure 2. It can be seen in the right-hand side of the figure that a total of 7.0 % of all filtrations of passion fruit juice over a prolonged period of time would result in $p > 0$ i.e. $J' < J_{critical}$, a membrane failure.

Table 2 presents 10 selected failures for analysis. Row 6 of Table 2 (**bold-text**) is the filtration scenario given in column 3 of Table 1. An advantage of this presentation is that the individual combination of each of the values of the parameters that gave rise to filtration failure can be identified. It is seen in the table for example, Row 11, $\Delta P$ = 100.698 kPa together with $t$ = 1728.9 s will result in failure of cross-flow membrane filtration of passion fruit juice.

## 4. DISCUSSION

If each simulation scenario is considered as a (batch-continuous) processing day, a *Fr 13* failure would occur (3,513/(50,000 days) *x* 365.25 days / year =) 26 times per year, on average i.e. approximately two per month despite good operations and maintenance. These predicted failures would not of course be expected to be equally spaced in time.

It is clear from Figure 2 and Table 2 that apparent steady batch-continuous cross-flow membrane filtration of passion fruit juice should be more correctly regarded as a mix of successful and unsuccessful (failed) operations. Significantly, this information is not available from the traditional SVA.

Table 1: Summary comparison of SVA and *Fr 13* for cross-flow membrane filtration of passion fruit juice

| Parameter | SVA | *Fr 13* model | |
|---|---|---|---|
| $\Delta P$ (kPa) | **100** | **98.77** | **RiskNormal** (100, 2.0, **RiskTruncate** (96, 104)) |
| $t$ (s) | **1800** | **1748.78** | **RiskNormal** (1800, 36, **RiskTruncate** (1728, 1872)) |
| $\mu_{T\,20\,^oC}$ (Pa s ) | 1002000 | 1002000 | constant |
| $A$ (m$^2$) | 0.056 | 0.056 | constant |
| $K_c$ (s m$^{-2}$) | 56000000 | 56000000 | constant |
| $Q$ (m$^3$ s$^{-1}$) | 0.0018 | 0.0018 | constant |
| $J_{critical}$ (m$^3$ m$^{-2}$ s$^{-1}$) | 0.00000313 | 0.00000313 | constant |
| $T$ ($^O$C) | 25 | 25 | constant |
| $\mu_T$ (Pa s ) | 812000 | 812000 | constant |
| $J'$ (m$^3$ m$^{-2}$ s$^{-1}$) | 0.0000031494 | 0.000003129 | Eq. (3) |
| $p$ (dimensionless) | - | **0.0851** | Eq. (5) |

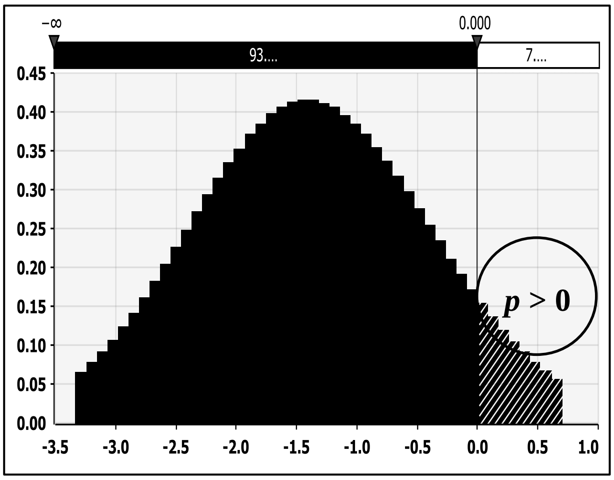


Figure 2: Simulation of the *Fr 13* risk factor ($p$) for cross-flow membrane filtration of passion fruit juice with 50,000 iterations

Table 2: 10 selected *Fr 13* failures from 3,513 in 50,000 scenarios of cross-flow filtration of passion fruit juice

| $\Delta P$ (kPa) | $t$ (s) | $J' \times 10^6$ (m$^3$ m$^{-2}$ s$^{-1}$) | $p$ |
|---|---|---|---|
| 101.2051 | 1750.8902 | 3.1933 | 0.0232 |
| 100.5250 | 1750.0103 | 3.1941 | 0.0489 |
| 100.3328 | 1749.3012 | 3.1948 | 0.0696 |
| 100.7358 | 1749.1922 | 3.1949 | 0.0727 |
| **98.7717** | **1748.7761** | **3.1953** | **0.0852** |
| 100.7191 | 1745.5379 | 3.1982 | 0.1802 |
| 98.8322 | 1743.4228 | 3.2002 | 0.2423 |
| 99.2111 | 1734.2506 | 3.2086 | 0.5121 |
| 99.4285 | 1729.2371 | 3.2133 | 0.6602 |
| 100.6980 | 1728.9496 | 3.2135 | 0.6681 |

Results from further investigation with the probability distributions used for $\Delta P$ and $t$, together with changes in the stdev used from 2 to 5, % about the means, did not meaningfully affect the number of predicted *Fr 13* failures in the cross-flow membrane filtration of passion fruit juice. The *Fr 13* model is therefore not sensitive to the variance about the mean value of the two key parameters.

Because the value of stdev used in the probability distributions is actually a quantitative measure of the quality, cost and accuracy of relevant filtration control (Davey 2011; Davey, Chandrakash and O'Neill 2013) this result underscores that increased control of $\Delta P$ and $t$ does not significantly affect the number of stochastic (random) *Fr 13* fouling failures in cross-flow filtration of passion fruit juice.

The number of *Fr 13* fouling failures would however be expected to be sensitive to the *%tolerance* used in defining the risk factor, $p$ i.e. the acceptable process risk.

Repeat simulations were therefore carried out for a range of values 2 ≤ *%tolerance* ≤ 10 on the risk factor, Eq. (4), and the results as number of filtration failures in 50,000 scenarios presented as Figure 3.

It is seen in the figure that the number of predicted failures decreases with increasing *%tolerance* until at a value 8 % there would be no failures in filtration of the passion fruit juice. This result is interpreted as the more stringent the tolerance on practical filtration the more failures in fouling.

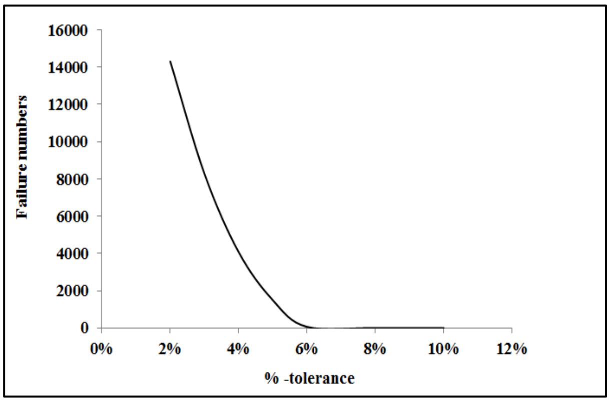


Figure 3: Effect of *%tolerance* on the number of filtration failures per 50,000 scenarios

A major advantage of the *Fr 13* model over the traditional SVA (with or without sensitivity analyses) (Sinnott 2005) is that all practically realizable process outcomes are actually computed. This results in significantly improved operational insight into vulnerability to failure of processes. The use of *Fr 13* simulations in second-tier computations to reduce vulnerability to failure due to stochastic effects by making changes to design and operation has been discussed elsewhere (Davey 2011; Davey, Chandrakash and O'Neill 2013).

At present, developments are continuing in *Fr 13* methodology to analyses of two or more inter-connected unit-operations to simulate progressively more complex plant and process interactions (Davey, Chandrakash and O'Neill 2014). A process with two or more inter-connected unit-operations is defined by Davey and co-workers as a global model.

## 5. CONCLUSIONS

A new *Fr 13* quantitative risk assessment has revealed that unexpected failure will occur in 7.0 % of all batch-continuous cross-flow membrane operations in otherwise well-operated plant used in clarification of passion fruit juice.

Cross-flow filtration is revealed to actually be a combination of successful and failed operations. This insight cannot be obtained by traditional methods.

The *Fr 13* risk model provides an advance over traditional methods in that all practical scenarios that can occur are computed.

## NOMENCLATURE

The equation number given after description refers to that in which the symbol is first used or defined.

| | |
|---|---|
| $A$ | Surface area, $m^2$, Eq. (2) |
| $J'$ | Permeate flux, $m^3 m^{-2} s^{-1}$, Eq. (1) |
| $J_{critical}$ | Permeate flux filtration success, $m^3 m^{-2} s^{-1}$, Eq. (4) |
| $J_0$ | Permeate flux clean water, $m^3 m^{-2} s^{-1}$, Eq. (1) |
| $K_c$ | Parameter (passion juice = 5.6 x $10^7$), s $m^{-2}$, Eq. (1) |
| $n$ | Fouling parameter ($n$ = 2 for cross-flow), Eq. (1) |
| n | Data (independent), Figure 1 |
| $p$ | Risk factor, (dimensionless), Eq. (4) |
| $Q$ | Water flow operational temperature, $m^3 s^{-1}$, Eq. (2) |
| $t$ | Filtration time, s, Eq. (1) |
| Greek | |
| $\Delta P$ | Transmembrane pressure, kPa, Eq. (2) |
| $\mu_T$ | Viscosity clean-water at temperature, Pa s, Eq. (2) |
| $\mu_{20\,^oC}$ | Viscosity clean-water at 20 $^OC$, Pa s, Eq. (2) |

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