NONLINEAR ANALYSIS FOR CHEMICAL PROCESSES BASED ON INCREMENTAL DISSIPATIVITY

Denny Hioe and Jie Bao
School of Chemical Engineering
The University of New South Wales
UNSW, Sydney NSW 2052, Australia
j.bao@unsw.edu.au

ABSTRACT
Many chemical processes exhibit strong nonlinear dynamic behaviours which may present significant challenges to process operation and control, including input and output multiplicities. Input multiplicity refers to the phenomenon where different inputs (control action) result in the same steady state process output, which is commonly encountered in biochemical reactors. A process with input multiplicity is not invertible and thus is difficult to control as a feedback controller essentially attempts to invert the process model. A process with output multiplicity may produce different steady-state output depending on its initial state, which is often observed in exothermic reactors and obviously leads to a difficulty in achieving the desired output. The work provides a link between these properties of nonlinear chemical processes and the concept of incrementally dissipative systems in nonlinear system theory. The quantitative analysis of the above two phenomena is proposed. Furthermore, a test of the feasibility of controlling nonlinear chemical processes using linear controllers is developed. Such a test is of practical significance because it is often attempted to control nonlinear chemical processes using linear controllers in control practice due to the simplicity in control system design. As the concept of dissipativity can be linked to thermodynamics, the dissipativity based analysis can be potentially related to process design and provides more insights into integrated process design and control.

INTRODUCTION
Operability analysis determines whether a process can be controlled effectively using a feedback control system. Upon the realization of the importance of simultaneous process design and control, such analysis plays an important role in the early stages of process design to reveal any potential operability problems, such as poor disturbance rejection, difficulty in changing operating conditions, or even plant stability. One of the most commonly researched methodologies for the analysis is the simultaneous optimization approach, which allows seamlessly integration of process and control design (Perkins & Walsh, 1996, Bahri et al., 1997). However, its implementation can be a challenging task, highly dependent on the size and complexity of the problem and by the limitations of the available computational algorithms (Sakizlis et al., 2004). As alternatives, a vast varieties of operability analysis based on open-loop models were proposed. These methods can be used without the knowledge of the closed-loop controllers structure, hence removing the arbitrary, time-consuming nature of simulation based approaches commonly applied in industry. However, many open-loop operability analysis methods are only applicable to linear processes. These include operability analysis methods developed based on non-minimum phase elements (Holt & Morari, 1985a, Holt & Morari, 1985b), condition numbers (Barton et al., 1991), process resilience indices (Cao et al., 1996, Morari, 1983) and relative gain array (RGA) (Bristol, 1966). Only a few methods are available for nonlinear processes. The process
characterization cube (Hernjak et al., 2004) was proposed to qualitatively estimate the controllability of nonlinear processes based on their degree of nonlinearity, process dynamics and degree of interaction between loops.

The few attempts at nonlinear operability analysis are mostly due to the complexities which are involved. It is however highly important since many chemical processes exhibit strong nonlinear behaviours which may lead to nontrivial problems for process control and operation. Among these problems, input and output multiplicity are among the most extensively studied due to their easy links to operability analysis. Input multiplicity refers to the phenomenon where different inputs result in the same steady state process output. This is commonly encountered in, for example, in biochemical reactors where different process operation temperatures (as control input to the process) yield the same growth of microorganism and thus the rate of reaction. In control, input multiplicity is a problem since it means that the process is invertible and therefore is not as easy to control by feedback control. On the other hand, a process with output multiplicity produces different steady-state output depending on its initial state. Such is commonly observed in exothermic reactors, where the same reactor conditions may result in different composition of products. Obviously, this is not desired for a process which is expected to produce constant expected yields.

In this paper, the concept of dissipative systems, which has been playing an important role in nonlinear systems analysis and feedback control design (Sepulchre et al., 1997), is used to formulate an alternative operability analysis for process systems. The links between dissipativity and dynamic operability of nonlinear process systems have been revealed in our previous study (Rojas et al., 2008) especially for the case of regulatory control problems. The current results rely on the extended concept of dissipativity, the incremental counterpart, to show the connection between dissipative systems and the nonlinear phenomena of input and output multiplicity.

The paper is organized as follows. First, the basic fundamentals of incremental dissipativity required for the main results are introduced. Then, the main results linking incremental dissipativity and input-output multiplicity are presented. A closed-loop operability analysis is also provided. Specifically, a condition which determines the existence of incremental stabilizing linear controllers for an incrementally dissipative system is shown. A possible numerical method to determine the dissipativity of a process based on Linear Differential Inclusion (LDI) is discussed. Finally, an illustrative example and a concluding remark are available at the end of the paper.

**INCREMENTAL DISSIPATIVITY AND STABILITY**

Consider a dynamic (nonlinear) process, denoted as $\Sigma$, given as follows:

\[
\begin{align*}
\dot{x} &= f(x, u) \\
y &= h(x, u)
\end{align*}
\]

Eq. 1

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^m$, and $y \in \mathbb{R}^p$ are the process states, inputs, and outputs respectively (all are functions of time) as in any usual control literatures. Assume that both functions $f$ and $g$ are continuously differentiable, i.e. $f, g \in C^1$.

**Definition 1 [Incremental dissipativity]** The dynamic system $\Sigma$ is said to be incrementally dissipative if there exists a $C^1$ storage function $V(x, \dot{x}) : \mathbb{R} \times \mathbb{R} \to \mathbb{R}^+$ such that for any two inputs $(u, \bar{u})$ the solutions of the system are $(x, \dot{x})$, and the respective outputs are $(y, \bar{y})$, the following inequality is satisfied:

...
\[ \tau \left( x, \dot{x} \right) = \frac{\partial \psi}{\partial x} f(x, u) + \frac{\partial \psi}{\partial \dot{x}} f(\dot{x}, u) \leq w(\Delta u, \Delta y) \]

where \( \Delta u = u - \bar{u} \) and \( \Delta y = y - \bar{y} \).

Depending on the forms of the incremental supply rate \( w(\Delta u, \Delta y) \), some special cases of incremental dissipativity can be defined. In this paper, motivated by (Hill & Moylan, 1977) the following incremental quadratic \( (Q, S, R) \)-supply is used.

\[ w(\Delta u, \Delta y) = \Delta y^T Q \Delta y + 2 \Delta y^T S \Delta u + \Delta u^T R \Delta u \]

where \( Q = Q^T \in \mathbb{R}^{p \times p} \), \( S \in \mathbb{R}^{p \times m} \), and \( R = R^T \in \mathbb{R}^{m \times m} \) are constant matrix.

The link between incremental dissipativity and incremental stability can be proposed in the proposed analysis. To define the latter concept, first consider the usual definitions of class \( \mathcal{K} \) and \( \mathcal{KL} \) functions:

**Definition 2** [Class \( \mathcal{K} \) function (Khalil, 2002)] A continuous function \( \alpha : [0, \alpha) \rightarrow [0, +\infty) \) is said to belong to class \( \mathcal{K} \) if it is strictly increasing and \( \alpha(0) = 0 \). It is said to belong to class \( \mathcal{K}_{\infty} \) if \( \alpha = +\infty \) and \( \alpha(r) \rightarrow +\infty \) as \( r \rightarrow +\infty \).

**Definition 3** [Class \( \mathcal{KL} \) function (Khalil, 2002)] A continuous function \( \beta : [0, \alpha) \times [0, +\infty) \rightarrow [0, +\infty) \) is said to belong to class \( \mathcal{KL} \) if, for each fixed \( s \), the mapping \( \beta(r, s) \) belongs to class \( \mathcal{K} \) with respect to \( r \) and, for each fixed \( r \), the mapping \( \beta(r, s) \) is decreasing with respect to \( s \) and \( \beta(r, s) \rightarrow 0 \) as \( s \rightarrow +\infty \).

Then incremental stability can be defined as follows:

**Definition 4** [Incremental global asymptotic stability (Angeli, 2002)] The dynamic system \( \Sigma \) is said to be incrementally globally asymptotically stable if there exists a function \( \beta \) of class \( \mathcal{KL} \) so that for all \( (x_0, \tilde{x}_0) \), \( u \) and \( t, t_0 \in \mathbb{R} \) such that \( t \geq t_0 \), the following holds:

\[ |\phi(t, t_0, x_0, u) - \phi(t, t_0, \tilde{x}_0, u)| \leq \beta(|x_0 - \tilde{x}_0|, t) \]

The notation \( \phi(t, t_0, x_0, u) \) is defined as the state at time \( t \) reached from initial state \( x_0 \) at initial time \( t_0 \) by applying the input \( u \) to the dynamic system \( \Sigma \). Conceptually, the above definition of incremental stability requires that the states of a system forced with the same input but starting from any different initial states to eventually converge.

The link between incremental dissipativity and incremental stability can be proposed following these two assumptions:

**Theorem 1** [Stability of an incrementally \((Q,S,R)\)-dissipative system] Consider a nonlinear incrementally \((Q,S,R)\)-dissipative system \( \Sigma \) as given by Eq. 1. Then the system is incrementally globally asymptotically stable if matrix \( Q \) is negative definite \( (Q < 0) \).

**INPUT AND OUTPUT MULTIPLICITY**

Using the definitions and theorem above, the link of incremental dissipativity and input-output multiplicity can be established. The following theorem states the connection between incremental dissipativity and output multiplicity.

**Theorem 2** [Incremental dissipativity and output multiplicity] The dynamic system \( \Sigma \) does not exhibit output multiplicity if it is \((Q,S,R)\)-incrementally dissipative with \( Q < 0 \).

**Proof.** If a system is asymptotically incrementally stable, i.e., \( Q < 0 \), then given two identical inputs, the system from different initial states will converge to the same
equilibrium point (or trajectory). By the definition of the output as a function, as given in Eq. 1, then the output $y$ of the system from different initial states will also converge. Therefore, incremental stability becomes a sufficient condition for the non-existence of output multiplicity. This concludes the proof of the theorem.

A similar argument can be proposed for input multiplicity by inverting the system. Here, the result is presented without proof (it is due to appear in a later publication).

**Theorem 3 [Incremental dissipativity and input multiplicity]** The system $\Sigma$ with $u \in \mathbb{R}^n$ and $y \in \mathbb{R}^n$ does not exhibit input multiplicity if it is $(Q,S,R)$-incrementally stable ($Q < 0$) and dissipative with respect to the following supply rate:

$$w_1(\Delta u, \Delta y) = \Delta u^T Q_2 \Delta u + 2\Delta u^T S_2 \Delta e + \Delta e^T S_1 \Delta e$$

Then the closed loop system is also incrementally $(Q,S,R)$-dissipative and satisfies the following incremental dissipativity condition:

$$\mathcal{V}(x, \dot{x}) \leq [\Delta u]^T \begin{bmatrix} Q_1 + R_2 & -S_1 + S_2^T \\ -S_1^T + S_2 & R_1 + Q_2 \end{bmatrix} [\Delta u] + 2[\Delta u]^T \begin{bmatrix} S_1^T \\ -R_x \end{bmatrix} [\Delta y] + \Delta y^T R_s \Delta y$$

where $\mathcal{V}(x, \dot{x}) = V_1(x, \dot{x}) + V_2(x, \dot{x})$ is the storage function while $x = [x_1^T \ x_2^T]^T$ and $\dot{x} = [x_1^T \ \dot{x}_2^T]^T$ are the composite state vectors respectively.

Using Theorem 1 and Proposition 1, the closed-loop system as depicted in Fig. 1 is incrementally stable if the following is satisfied.

$$Q_{c1} \triangleq \begin{bmatrix} Q_1 + R_2 & -S_1 + S_2^T \\ -S_1^T + S_2 & R_1 + Q_2 \end{bmatrix} < 0$$

Eq. 2

Consider the feedback control system illustrated in Fig. 1. Also consider the results of Proposition 1. The operability analysis of the nonlinear process $\Sigma_2$ with known matrices $Q_2, S_2$ and $R_2$ can be formulated as an optimization problem of finding $Q_2, S_1$ and $R_1$ matrices of the controller $\Sigma_1$ to achieve the best control performance based on a certain
performance criterion subject to Inequality (2). Controller $\Sigma_1$ can be any incrementally $(Q, S, R)$-dissipative system, even a linear $(Q, S, R)$-dissipative system with appropriate $Q_2, S_2$, and $R_2$ matrices to satisfy Inequality (2).

Such a controller is not unique. However, if it is assumed that the controller is linear and stable, it is possible to derive a sufficient condition on the existence of a linear controller $\Sigma_1$ that satisfies a given incremental $(Q_1, S_1, R_1)$-dissipativity condition:

**Theorem 4 [Existence of a linear incrementally $(Q,S,R)$-dissipative system]** For given matrices $Q = Q^T \in \mathbb{R}^{p \times p}$, $S = S^T \in \mathbb{R}^{m \times m}$, and $R = R^T \in \mathbb{R}^{m \times m}$, a stable and incrementally $(Q, S, R)$-dissipative linear system $\Sigma := (A, B, C, D)$ exists if:

$$ R + S^T D + D^T S + D^T Q D \succeq 0 $$

This theorem can be used as a constraint in an optimization problem of finding $Q_1, S_1$, and $R_2$ matrices of the linear controller $\Sigma_1$. Using this theorem, the existence of controller $\Sigma_1$ is always guaranteed.

For the existence of the controller the following feasibility study can be performed:

**Problem** For a nonlinear process $\Sigma_2$ with known matrices $Q_2, S_2$, and $R_2$, test the feasibility of:

$$ Q_{21} \triangleq \begin{bmatrix} Q_2 + R_2 & -S_1 + S_2^T \\ -S_1^T + S_2 & R_1 + Q_2 \end{bmatrix} \prec 0 $$

$$ R + S^T D + D^T S + D^T Q D \succeq 0 $$

The above optimization problem is nonlinear and hence needs to be solved using nonlinear optimization methods (e.g., successive semi-definite programming). However, if the controller feed-through matrix $D_2$ is given, the above optimization problems becomes convex and can be solved numerically using any semi-definite programming (SDP) software package, such as SDPT3 (Toh et al., 1999).

**ESTIMATING $(Q,S,R)$ MATRICES OF A NONLINEAR PROCESS**

The nonlinear analysis proposed in the previous section requires the information on the dissipativity of a nonlinear system (i.e., $Q, S$ and $R$ matrices). One of the ways to determine the supply rate of a general nonlinear system is based on Linear Differential Inclusion (LDI), which will be briefly introduced as follows. More detailed discussions on this topic can be found in (Boyd, 1994).

Consider a nonlinear process $\Sigma$ as given in Eq. 1. Suppose that for each $x(t)$ and $u(t)$ there exists a matrix $G(x, u) \in \Omega$ such that:

$$ \begin{bmatrix} f(x, u) \\ h(x, u) \end{bmatrix} = G(x, u) \begin{bmatrix} x' \\ u \end{bmatrix} $$

Then every trajectory of the nonlinear process is also a trajectory of the Linear Differential Inclusions (LDI) defined by:

$$ \begin{bmatrix} \dot{x} \\ y \end{bmatrix} \in \Omega \begin{bmatrix} x' \\ u \end{bmatrix} $$

where $\Omega \in \mathbb{R}^{(n+m) \times (n+m)}$. If every trajectory of the LDI defined by $\Omega$ has a certain property (e.g., asymptotic stability) then every trajectory of the nonlinear system $\Sigma$ will also have that same property. Where the difference of trajectories is concerned, the above condition can be simplified as follows:
\[
\left[ \begin{array}{c}
\Delta x \\
\Delta y
\end{array} \right] \in \text{co} \Omega \left[ \begin{array}{c}
\Delta x \\
\Delta y
\end{array} \right]
\]

where \( \text{co} \) denotes the convex hull of the set.

LDI can be described in various ways. One of the most common ways is to describe the LDI using a polytope. In this case, \( \Omega \) can be represented by the polytope’s vertices given as follows:

\[
\Omega = \text{co} \left\{ \left[ \begin{array}{c}
A_1 \\
B_1 \\
C_1 \\
D_1
\end{array} \right], \left[ \begin{array}{c}
A_2 \\
B_2 \\
C_2 \\
D_2
\end{array} \right], \ldots, \left[ \begin{array}{c}
A_p \\
B_p \\
C_p \\
D_p
\end{array} \right] \right\}
\]

By the definition of convex hull, the above equation can be understood as follows: let \( \alpha_i = (A_i, B_i, C_i, D_i) \) be the representation on the vertices, then for any \( \alpha = (A, B, C, D) \in \Omega \), it is possible to write \( \alpha = \sum_{i=1}^{p} \mu_i \alpha_i \) with \( \mu_i \geq 0 \) for all \( i \) and \( \sum_{i=1}^{p} \mu_i = 1 \).

The following theorem provides a necessary and sufficient condition for a nonlinear process \( \Sigma \) to be incrementally \((Q,S,R)\)-dissipative.

**Theorem 5 [Polytopic Incremental Dissipativity]** Consider a nonlinear process \( \Sigma \) that can be represented by PLDI. Consider the quadratic storage function \( V(x,z) = \Delta x^T P \Delta x \). A necessary and sufficient condition for the nonlinear process to be incrementally \((Q,S,R)\)-dissipative is:

\[
\psi_i = \left[ \begin{array}{c}
A_i^T P + PA_i - C_i^T QC_i \\
PB_i - C_i^T \left[ S + Q D_i \right] \\
-D_i^T \left[ S + D_i^T Q D_i \right]
\end{array} \right] \leq 0
\]

for all \( \left[ \begin{array}{c}
A_i \\
B_i \\
C_i \\
D_i
\end{array} \right] \in \Omega \)

where \( P = P^T \) and \( (A_i, B_i, C_i, D_i) \) are the state space representation matrices of the system at vertex \( i \).

**DISCUSSION**

Incremental dissipativity is a stronger condition compared to (the conventional) dissipativity. The incremental version requires the dissipativity condition to be satisfied for any arbitrary feasible operating point, namely \( \hat{x}, \hat{u} \) and \( \hat{y} \). Based on this fact, the use of incremental definition implies that the operability test is global irrespective of a reference point. This fact is very useful for input-output multiplicity results. It can be argued that using the conventional definition, the existence input-output multiplicity can be contradicted using asymptotic property. That is, if the (inverse) system is asymptotic stable, it leads to the non-existence of (input) output multiplicity. However, such property is only true with respect to a known equilibrium. If the equilibrium is changed, then the results cannot be guaranteed anymore. In contrast, using the incremental definition, it can be guaranteed that input-output multiplicity is absent globally irrespective of a known reference point. This property makes incremental dissipativity a suitable candidate for operability analysis of systems which are subject to different operating points, for example, to force a desired variation in the product. Combined with the proposed LDI approach, it is possible to determine such absence in a bounded operating region of interest.

The link between incremental dissipativity and incremental stability also has the potential to extend the analysis to servo control problems (i.e., reference tracking).
Consider an incrementally dissipative and incrementally stable system. One can define the desired stable operating trajectories starting from a particular equilibrium point. By the definition of incremental stability, the system trajectory starting from any initial states will converge to the same operating points or trajectories. This point will be made stronger in a later publication.

Note that although linearisation methodology is relied on, the operability analysis method proposed in this paper goes beyond the operability analysis based on the dissipativity of a linearised model. The operability analysis based on the dissipativity of a linearised model is only valid around the operating point where the linearised model is obtained. The proposed method is developed based on incremental dissipativity properties over a predefined operating region. This means the operability analysis is valid not only at one particular operating point but also at all other operating points inside the operating region.

Under the current numerical approach, the validity of the operability analysis is only guaranteed when the system stays in the region defined by the polytope. It is, of course, more convenient to choose a larger region to guarantee that the system trajectory belongs in the region at all times. However, with a larger region, the dissipativity constraints may be very restrictive such that it is impossible to guarantee incremental stability using a linear $(Q,S,R)$-dissipative controller. Therefore, it is essential to impose certain conditions on the closed loop system gain with respect to disturbances inside the region when dealing with regulatory problem at multiple equilibriums or on the tracking trajectory to ensure that the evolution of the system is contained by the region. The latter can be achieved by allowing a relatively slow and smooth tracking. Observe that the above limitation is not introduced by the dissipativity-based operability analysis itself, but rather caused by the linear differential inclusion approach that determines the incremental dissipativity numerically.

The proposed approach can also be used to analyse the adequacy of a linear control for a nonlinear process. The answer is commonly related to the problem of quantifying the degree of nonlinearity of the nonlinear process. However, as it has been recently recognized, the degree of nonlinearity of the process does not necessarily lead to the poor performance of the closed loop system equipped with a linear controller (Sepulchre et al., 1997). This implies that a highly nonlinear process may not always be difficult to control using linear control as long as the corresponding dissipativity and stability conditions are satisfied.

**ILLUSTRATIVE EXAMPLE**

Consider the following dimensionless model of a continuous stirred tank reactor (CSTR) in which a first order irreversible exothermic reaction occurs. The state space model of the reactor is taken from (Calvet & Arkun, 1988). For the purpose of the current study, however, the effect of disturbances is neglected.

\[
\dot{x}_1 = -x_1 + Da(1 - x_2)\exp\left(\frac{x_2}{(x_2/\gamma) + 1}\right) \\
\dot{x}_2 = -x_2 + DaB(1 - x_2)\exp\left(\frac{x_2}{(x_2/\gamma) + 1}\right) - \beta(x_2 - x_{2e}) + \beta u \\
y = x_2
\]

where $x_1, x_2$ and $u$ are dimensionless variables (normalized with respect to the inlet values (see (Calvet & Arkun, 1988)), and thus may not be in the range 0.0-1.0) be of the composition of reactant, reactor temperature and coolant temperature respectively. The
values of these variables represent the normalized (relative) deviation from the nominal values (e.g., $u = 0$ indicates a nominal coolant temperature is used). The parameters are defined in (Calvet & Arkun, 1988). The objective is to control the reactor temperature $x_2$ by manipulating the coolant temperature $u$. With $B = 6$, $\beta = 0.3$, $\gamma = 20$, $Da = 0.072$, and $x_{2e} = 0$, the following three equilibrium points of the open-loop system with a nominal coolant temperature (i.e., $u = 0$) are observed:

Equilibrium A : $(x_{1e}, x_{2e}) = (0.144, 0.886)$
Equilibrium B : $(x_{1e}, x_{2e}) = (0.447, 2.7517)$
Equilibrium C : $(x_{1e}, x_{2e}) = (0.7646, 4.705)$

where equilibria A and C are stable and equilibrium B is unstable.

![Fig. 2: Phase plane plot of the CSTR model](image-url)
Consider an operating region defined by $0.1 \leq x_2 \leq 0.8$ and $0.8 \leq x_2 \leq 5.0$. Around this operating region, the phase plane plot is shown in Fig. 2 which clearly shows the open loop process has output multiplicity. The forced equilibrium manifold of the system is illustrated in Fig. 3. The dynamic model of the nonlinear CSTR process is then represented using a polytopic linear differential inclusion (PLDI) based on the vertices of the polytope shown in Fig. 3. The incremental stability condition, if satisfied, will drive the states (close) to the equilibrium manifold. Therefore, the polytope is determined near the equilibrium manifold to ensure its inclusion of the state evolution. This decreases the conservativeness of the numerical PLDI analysis as previously discussed.

By performing a feasibility study on the open loop system, that is to test Theorem 5 with constraint $Q < 0$, it can be shown that the problem is infeasible, indicating a possibility of output multiplicity (which exists in this case). This output multiplicity can be removed by an incrementally dissipative controller that achieves closed-loop incremental stability. By pre-determining $D_c$, the convex problem presented in the Closed-loop Analysis section is solved using SDPT3 software. The following supply rate for the process system is feasible:

\[
Q = 0.2487, \quad S = 0.0182, \quad R = 0.0001
\]

The controller that achieves incremental stability can have the following feasible supply rate:

\[
Q_c = -1.1934 \times 10^{-4}, \quad S_c = 0.0183, \quad R_c = -0.3510
\]

The controller form can be obtained by using Theorem 4. One of the controllers that satisfies the above incremental dissipativity condition has the following state space representation:

\[
A_c = -1, \quad B_c = 1, \quad C_c = 250, \quad D_c = 10
\]

The results of this short case study show how the analysis based on incremental dissipativity can be used to guarantee incremental stability, thereby eliminating any possible output multiplicity, which may lead to operability issues.
CONCLUSION

In this paper, we developed the link between incremental dissipativity and incremental stability. These concepts are closely related to the input and output multiplicity, which may not be desirable from the point of view of control. A sufficient condition for the non-existence of both phenomena is established. To facilitate the dissipativity based analysis, a numerical method to determine the incremental dissipativity of nonlinear processes has been developed based on Linear Differential Inclusion (LDI).

ACKNOWLEDGEMENT

This work is partially supported by the ARC Discovery Project DP1093045. The first author would like to acknowledge the financial support of the APA scholarship as well as the ESA and UNSW Excellence awards provided by UNSW.

REFERENCES


**BRIEF BIOGRAPHY OF PRESENTER**

Denny Hioe received a B.E. (Hons I and the University Medal) in Chemical Engineering in 2010 from the University of New South Wales. He is currently a PhD candidate at the same university. His research interests include nonlinear system analysis based on dissipative systems, dissipativity analysis based on thermodynamics, network theories for chemical engineering, and plantwide dynamic operability analysis.