DEVELOPMENTS IN FOOD SCIENCE 36

AUTOMATIC CONTROL OF FOOD AND BIOLOGICAL PROCESSES

ELSEVIER SCIENCE B.V.
Sara Burgerhartstraat 25
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

Library of Congress Cataloging-in-Publication Data

International Symposium on the Automatic Control and Optimisation of Food Processes (3rd : 1994 : Paris, France)
Automatic control of food and biological processes : proceedings of the ACoFoP III Symposium, Paris, France, 25-26 October, 1994 / edited by J.J. Bimbenet, E. Dumoulin, and G. Trystram.
p. cm. -- (Developments in food science ; 36)
Includes bibliographical references and index.
ISBN 0-444-81959-2
1. Food industry and trade--Automation--Congre. 2. Automatic control--Congresses. I. Bimbenet, J. J. (Jean Jacques) II. Dumoulin, E. III. Trystram, G. IV. Title. V. Series.
TP372.8.I56 1994
664'.02--dc20 94-36658
CIP

ISBN: 0-444-81959-2

This book is printed on acid-free paper.

Printed in The Netherlands

DEVELOPMENTS IN FOOD SCIENCE

Volume 1	J.G. Heathcote and J.R. Hibbert Aflatoxins: Chemical and Biological Aspects
Volume 2	H. Chiba, M. Fujimaki, K. Iwai, H. Mitsuda and Y. Morita (Editors) Proceedings of the Fifth International Congress of Food Science and Technology
Volume 3	I.D. Morton and A.J. MacLeod (Editors) Food Flavours Part A. Introduction Part B. The Flavour of Beverages Part C. The Flavour of Fruits
Volume 4	Y. Ueno (Editor) Trichothecenes: Chemical, Biological and Toxicological Aspects
Volume 5	J. Holas and J. Kratochvil (Editors) Progress in Cereal Chemistry and Technology. Proceedings of the VIIth World Cereal and Bread Congress, Prague, 28 June–2 July 1982
Volume 6	I. Kiss Testing Methods in Food Microbiology
Volume 7	H. Kurata and Y. Ueno (Editors) Toxigenic Fungi: Their Toxins and Health Hazard. Proceedings of the Mycotoxin Symposium, Tokyo, 30 August–3 September 1983
Volume 8	V. Betina (Editor) Mycotoxins: Production, Isolation, Separation and Purification
Volume 9	J. Holló (Editor) Food Industries and the Environment. Proceedings of the International Symposium, Budapest, Hungary, 9–11 September 1982
Volume 10	J. Adda (Editor) Progress in Flavour Research 1984. Proceedings of the 4th Weurman Flavour Research Symposium, Dourdan, France, 9–11 May 1984
Volume 11	J. Holló (Editor) Fat Science 1983. Proceedings of the 16th International Society for Fat Research Congress, Budapest, Hungary, 4–7 October 1983
Volume 12	G. Charalambous (Editor) The Shelf Life of Foods and Beverages. Proceedings of the 4th International Flavor Conference, Rhodes, Greece, 23–26 July 1985
Volume 13	M. Fujimaki, M. Namiki and H. Kato (Editors) Amino-Carbonyl Reactions in Food and Biological Systems. Proceedings of the 3rd International Symposium on the Maillard Reaction, Susuno, Shizuoka, Japan, 1–5 July 1985
Volume 14	J. Škoda and H. Škodová Molecular Genetics. An Outline for Food Chemists and Biotechnologists
Volume 15	D.E. Kramer and J. Liston (Editors) Seafood Quality Determination. Proceedings of the International Symposium, Anchorage, Alaska, U.S.A., 10–14 November 1986
Volume 16	R.C. Baker, P. Wong Hahn and K.R. Robbins Fundamentals of New Food Product Development
Volume 17	G. Charalambous (Editor) Frontiers of Flavor. Proceedings of the 5th International Flavor Conference, Porto Karras, Chalkidiki, Greece, 1–3 July 1987
Volume 18	B.M. Lawrence, B.D. Mookherjee and B.J. Willis (Editors) Flavors and Fragrances: A World Perspective. Proceedings of the 10th International Congress of Essential Oils, Fragrances and Flavors, Washington, DC, U.S.A., 16–20 November 1986
Volume 19	G. Charalambous and G. Doxastakis (Editors) Food Emulsifiers: Chemistry, Technology, Functional Properties and Applications
Volume 20	B.W. Berry and K.F. Leddy Meat Freezing. A Source Book

Volume 21	J. Davídek, J. Velíšek and J. Pokorný (Editors) Chemical Changes during Food Processing
Volume 22	V. Kyzlink Principles of Food Preservation
Volume 23	H. Niewiadomski Rapeseed. Chemistry and Technology
Volume 24	G. Charalambous (Editor) Flavors and Off-Flavors '89. Proceedings of the 6th International Flavor Conference, Rethymnon, Crete, Greece, 5–7 July 1989
Volume 25	R. Rouseff (Editor) Bitterness in Foods and Beverages
Volume 26	J. Chelkowski (Editor) Cereal Grain. Mycotoxins, Fungi and Quality in Drying and Storage
Volume 27	M. Verzele and D. De Keukeleire Chemistry and Analysis of Hop and Beer Bitter Acids
Volume 28	G. Charalambous (Editor) Off-Flavors in Foods and Beverages
Volume 29	G. Charalambous (Editor) Food Science and Human Nutrition
Volume 30	H.H. Huss, M. Jakobsen and J. Liston (Editors) Quality Assurance in the Fish Industry. Proceedings of an International Conference, Copenhagen, Denmark, 26–30 August 1991
Volume 31	R.A. Samson, A.D. Hocking, J.I. Pitt and A.D. King (Editors) Modern Methods in Food Mycology
Volume 32	G. Charalambous (Editor) Food Flavors, Ingredients and Composition. Proceedings of the 7th International Flavor Conference, Pythagorion, Samos, Greece, 24–26 June 1992
Volume 33	G. Charalambous (Editor) Shelf Life Studies of Foods and Beverages. Chemical, Biological, Physical and Nutritional Aspects
Volume 34	G. Charalambous (Editor) Spices, Herbs and Edible Fungi
Volume 35	H. Maarse and D. G. van der Heij (Editors) Trends in Flavour Research. Proceedings of the 7th Weurman Flavour Research Symposium, Noordwijkerhout, The Netherlands, 15-18 June 1993
Volume 36	J. J. Bimbenet, E. Dumoulin and G. Trystram (Editors) Automatic Control of Food and Biological Processes. Proceedings of the ACoFoP III Symposium, Paris, France, 25–26 October 1994

INTRODUCTION

Process control is one of the most important tasks of the food and biological industries. The need for high quality levels, product properties, hygiene, productivity requirements, etc., are objectives that can be obtained through better control of the process. The nature of the decisions necessary to ensure the best performance is very complex. Operators cannot involve themselves with all aspects of the process and product. After a long period of mechanization, the food and biological industries appear to be a good subject/(candidate?) for the integration of more sophisticated tasks using control science and technology. Many difficulties can be expected: complexity of raw materials and changes in their characteristics, coupling of continuous and batch processes, lack of sensors, poor knowledge of the dynamics of phenomena, hygiene requirements, and equipment constraints, etc.

From another point of view, there has been great progress in the field of control science. More and more sophisticated sensors are available every day. New, non-linear, model based strategies and adaptive control laws are being studied by teams working specifically on the control process. Computer technology applications have become available for industrial implementation. Consequently, much progress has been made in understanding the phenomena that occur during processes, specifically in control of the transient state through the dynamic behaviour of unit operations. Problems found in the food and biological industries seem to be a good area for control applications.

Despite the above, progress in industry, especially that of the food industry, is not thought about as much as it should be. An international conference is a way of establishing contact between those in research and industry, and to promote the diffusion of research results in industry. It allows demonstration of recent results and discussion on their applications. It also presents an opportunity to present open problems. This was the purpose of the ACOFOP I, II and III Symposia. The chapters of this book are written by contributors to the third one, held in Paris in 1994, and are dedicated to recent progress in the field of automation of food and biological processes. It is also an opportunity to put together a wide variety of papers covering this important subject.

The book is divided into four parts. The first part is dedicated to sensor problems. Papers present new realizations, applications and discussions on the importance of sensors for controlling the process and monitoring product quality. The second part presents results and development concerning modelling, especially dynamic modelling of food and biological processes. Some modelling applications are discussed using simulation, particularly the importance of estimation for non-measurable parameters. Progress in development of artificial intelligence tools is presented. The third, most important part of the book concerns the control process itself. It is an opportunity to bring together the presentation of many algorithms for unit operation control in such different units as dryers or fermenters. The last part is dedicated to computer aided applications in the field of control, including supervision and operator decision aided systems.

More generally, many applications at the pilot or industrial scale are presented in order to establish the feasibility of automatic control of food and biological processes. This book is, therefore, a compilation of important new results in this field.

We would like to thank all contributors to the symposium, especially those who contributed chapters on the presentation of methods, tools and results. It is also important to thank the IPA Company for the material support for organization and, last but not least, the sponsors of the symposium.

J.J. Bimbenet
E. Dumoulin
G. Trystram

CONTENTS

Introduction vii

PART A - SENSORS AND MEASUREMENTS

Software Sensors and Adaptive Control in Biotechnology 3
D. DOCHAIN

Process Control in the Sugar Industry by FT-IR Spectrometer Coupled with an ATR Accessory 11
V. BELLON-MAUREL and G. TRYSTRAM

On-line Image Acquisition for Microscopic Study of Plant Tissues During Osmotic Dehydration 19
H.C. CHU and M. LE MAGUER

Recent Developments of Indirect Measurements and Software Sensors for Bioprocesses Control 27
G. CORRIEU, E. LATRILLE, D. PICQUE and B. PERRET

Rapid Fat and Water Determination by Nuclear Magnetic Resonance for Drying and Fat Coating Control of Extrudates 35
A. DAVENEL and P. MARCHAL

An Evaluation of Infrared Non-contact Thermometers for Food Use 43
J.A. EVANS, S.L. RUSSELL and S.J. JAMES

Apple Destruction Caused by Firmness Test 51
A. FEKETE, J. FELFÖLDI and E. GYŐRI

Light Losses in a Fiber Optics Connection to a Luminometer 59
P. GRENIER, L. DUSSERE-BRESSON, V. ISSERT, J.-F. BONICEL, J.-M. FATOU, V. BELLON-MAUREL and B. GOUTEYRON

Flow Injection Determination of Reducing Sugar in Wine in a Wide Concentration Range Using a Dialysis Unit and a Stream Splitting 67
J.L.F.C. LIMA, O.B.A.O NEVES and A.O.S.S. RANGEL

New Physical Methods and Systems for Automated Researching of the State of Plants and Seeds 75
J.S. LISKER

Biosensor for On-line Monitoring of Penicillin During its Production by Fermentation 83
H. MEIER and C. TRAN-MINH

Evaluation of Sensors to Monitor Mixed Coagulation 89
D. PICQUE, E. LATRILLE, B. PERRET, F. REMEUF and G. CORRIEU

Texture Characterization of Extruded Food Products 99
M.N. PONS and H. VIVIER

Shape Characterization of Particulate Food Products 107
M.N. PONS, C. GRAF and H. VIVIER

Online Measurement of Physical and Chemical Process Parameters to Achieve Improved Control, Feedback Control, and Time Optimization of Fermentation Processes Using Neural Networks and Fuzzy Logic 115
U. SCHRADER, U. HEGE, T. ENDERS and V. DENK

Estimation of a Solid Surface Temperature during a Flash Vapour Treatment 123
O. TECHASENA and D. FLICK

Dynamic Control of Inversion Operation in the Xixona Turrón Manufacture Process 131
N. MARTÍNEZ, A. CHIRALT and P. FITO

PART B - ESTIMATION AND MODELLING

Artificial Intelligence in Bioprocess Modelling, Estimation and Control 143
S. LINKO, Y.-H. ZHU, T. EERIKÄINEN, T. SIIMES and P. LINKO

Dynamic Simulation and Real Time Expert System for Food Freezing Process Control 159
S. BANOUNE and D. DEPEYRE

Dynamic Simulation for Sugar Crystallization Plant Control. A Comparative Study of Specific and Generalized Approaches 167
M.BOUAMRANI, A. ISAMBERT and D. DEPEYRE

Modelling and Dynamic Simulation of Cooling Crystallization of Sucrose 175
Z. BUBNÍK and P. KADLEC

Process Modelling of Pasta Drying 183
B. DE CINDIO, B. BRANCATO and C.M. POLLINI

The Use of Computational Fluid Dynamics Modelling in Air Flow Problems in the Food Industry 191
A.J. GIGIEL, M.J. SWAIN and S.J. JAMES

Modelling Air Movement and Temperature Control in Chilled Distribution Vehicles 199
S.J. JAMES, A.J. GIGIEL and S.E. PARRY-JONES

Modelling of a Continuous Peanut Roasting Process 207
J.J. LANDMAN, V.J. DAVIDSON, R.B. BROWN, G.L. HAYWARD and L. OTTEN

Temperature and Velocity Fluctuations in Steady State Collinear Ohmic Heaters . . . 215
F.L. MULLER, J.P. PAIN and P. VILLON

Experimental Study and Modeling of the Wood Retification Process 227
J.R. RAJOHNSON, R. GUYONNET and B. GUILHOT

Modelling of Biological Suspension Microfiltration Using Neural Networks 235
F. RENÉ, E. LATRILLE and C. RENOU

Hydrodynamic Modelling of a Packed-bed Bioreactor Used in the Brewing Industry with a View to Process Control 243
P. SARRAUT, A. CHÉRUY, M. LENOEL, M. SHINGLETON and L. RUHAUT

PART C - AUTOMATIC CONTROL

Model Based Predictive Control 253
J. RICHALET

Control Strategy of the Refrigeration Process: Fruit and Vegetables Conditioned in a Pallet 265
G. ALVAREZ and G. TRYSTRAM

Automatic Control of Fed-batch Baker's Yeast Cultivation 273
A.A. AMELKIN

Automatic Control of Aerobic and Anaerobic Respiration Rates of Fruits Stored in Refrigerated and Controlled Atmospheres 281
G. ANDRICH, A. ZINNAI, S. BALZINI, S. SILVESTRI and R. FIORENTINI

Study and Control of the Dynamics of Drying Processes 289
F. COURTOIS and G. TRYSTRAM

Automatic Control of a Crossflow Microfiltration Pilot Plant at Low Transmembrane Pressure 297
M. DECLOUX, M. DORNIER, C. GENESTE, F. PROTHON and G. TRYSTRAM

Development of a Neural Controller Based upon Manual Experiment. Application to a Batch Reactor 305
J.L. DIRION, M. CABASSUD, M.V. LE LANN and G. CASAMATTA

Control of Material Moisture Content and Temperature in Conveyor-belt Dryers . . 313
C.T. KIRANOUDIS, Z.B. MAROULIS, D. MARINOS-KOURIS and G.D. SARAVACOS

Neural Control of Fed-batch Baker's Yeast Fermentation 321
A. KOSOLA and P. LINKO

Control of the Cooling Rate during Freezing: Which Cooling Rate and Which Control Parameters? Application to Bread Dough Freezing 329
A. LE BAIL and G. CORNIER

Model Based Control of a Multipurpose Batch Reactor with a Variable Control Structure 337
Z.H. LIU and S. MACCHIETTO

Experience with Automatic Control of Biscuit and Cracker Ovens 345
I. McFARLANE

An On-line Control Procedure for Predicting Time/Temperature History using a Heat Flux Sensor Mounted on the Container Outside Surface of a Packaged Conduction Heated Food 351
T. MIHORI, L. XIE and H. WATANABE

Development of Upgraded Process Control Applications in SMEs in the Food Sector 357
B. O'CONNOR

Automatization of a Drum Dryer for the Food Industry 359
G. RODRIGUEZ, J. VASSEUR and G. TRYSTRAM

The Application of Mathematical Models to the Control of In-container Thermal Processing 367
G.M. SCOTT and G.S. TUCKER

An On-line Control for the Optimal Sterilization of a Cylindrical Packaged Conduction-heated Food with Unknown Surface Heat Transfer Coefficients and Unknown Thermal Diffusivities 375
H. WATANABE, L. XIE and T. MIHORI

PART D - SIMULATION, OPTIMIZATION AND COMPUTER-AIDED METHODS

What is Behind Cognitive Computing? A Survey 383
F. BECHMANN and T. RÄDLER

Computer Aided Process Design for Minimally Processed Foods 391
T. MARTENS, M. SCHELLEKENS, B. NICOLAI and J. DE BAERDEMAEKER

Energy Integration of Brewery Operations 401
D. MIGNON and J. HERMIA

Optimal Operation of a pH-controlled Fed-batch Gluconate Production by Immobilised *Aspergillus niger* 409
M. MORESI, E. PARENTE and A. RICCIARDI

A Graphical Simulation Environment for the Visualization of Conductive Heat Transfer in Foods 417
B.M. NICOLAÏ, E. MAES, M. SCHELLEKENS, T. MARTENS and J. DE BAERDEMAEKER

Use of Artificial Intelligence for Resources Optimization in the Food Industry. A Winemaking Example 425
V. NIVIÈRE, P. VILETTE, P. GRENIER, J.-M. ROGER, F. SEVILA and M. OUSSALAH

Simulation of Food Processes. A Tool for Training Operators in Production 433
C. SKJÖLDEBRAND, B. SUNDSTRÖM , H. JANESTAD and C.-G. ANDERSSON

Supervision of Food Processes 441
G. TRYSTRAM, M. DANZART, R. TREILLON and B. O'CONNOR

Optimal Operation Policies in Food Processing 449
A.J.B. VAN BOXTEL

PART A
SENSORS AND MEASUREMENTS

Automatic Control of Food and Biological Processes
J. J. Bimbenet, E. Dumoulin and G. Trystram (eds)

SOFTWARE SENSORS AND ADAPTIVE CONTROL IN BIOTECHNOLOGY

D. Dochain
Chercheur qualifié FNRS, Cesame, Université Catholique de Louvain
Bât. Euler, av. G. Lemaître 4-6, 1348 Louvain-La-Neuve, Belgium

Abstract

This paper presents a brief survey about recent approaches of model-based monitoring and control of bioreactors, based on material balances and which accounts for the uncertain kowledge about the process kinetics.

1 Introduction

Automatic control of industrial biotechnological processes is still developing slowly. There are two main reasons for this : the internal working and dynamics of these processes are as yet badly grasped; another essential difficulty lies in the absence, in most cases, of cheap and reliable instrumentation suited to real-time monitoring. The classical monitoring and control methods do not prove very efficient to tide over these basic difficulties. Monitoring or control algorithms will prove to be efficient if they are able to incorporate the important well-known information on the process while being able to deal with the missing informations (lack of on-line measurements, uncertainty on the dynamics, ...) in a "robust" way, i.e. such that these missing informations will not significantly deteriorate the control performance of the process. In this paper, it is shown how to incorporate the well-known knowledge about the dynamics of biochemical processes (basically, the reaction network and the material balances) in monitoring and control algorithms which are moreover capable of dealing with the process uncertainty (in particular on the reaction kinetics) by introducing, for instance in the control algorithms, an adaptation scheme). A key reference to this paper is the book ([1]). The paper is organized as follows. In Section 2, we shall introduce the general dynamical model for stirred tank bioreactors and illustrate it with two fermentation examples (intracellular production of biodegradable polymers (poly-β-hydroxybutyric acid (PHB)), anaerobic digestion). Section 3 is concerned with model order reduction. Section 4 will deal with the design of asymptotic observers for the process components. Finally, Section 5 will present the design of adaptive linearizing controllers for bioprocesses based on a reduced order model of the process.

2 General Dynamical Model

A biotechnological process can be defined as a set of M biochemical reactions involving N components. The dynamical model of a bioprocess in a stirred tank reactor can be

deduced from mass balance considerations and written in the following compact form :

$$\frac{d\xi}{dt} = -D\xi + Kr + F - Q \tag{1}$$

where ξ is the vector of the bioprocess component ($\dim(\xi) = N$), K is the yield coefficient matrix ($\dim(K) = N \times M$), r is the reaction rate vector ($\dim(r) = M$), F is the feed rate vector and Q the gaseous outflow rate vector ($\dim(F) = \dim(Q) = N$). The model (1) has been called the *General Dynamical Model* for stirred tank bioreactors (for further details, see [1]).

2.1 Example #1 : PHB Production Process

Let us first consider the production of poly-β-hydroxybutyric acid (PHB), which is a biodegradable polymer. The PHB can be produced in an aerobic culture of *Alcaligenes eutrophus*, and the production may follow two metabolic pathways : the first metabolic pathway for the production of PHB is growth associated (with three limiting substrates : oxygen, a source of carbon (e.g. fructose or glucose) and nitrogen (ammonia)) and characterized by a very low yield; the second metabolic pathway for the production of PHB is non-growth associated, where the biomass plays simply the role of a catalyst, and is completely inhibited by nitrogen. Therefore the production of PHB can be schematized by the following reaction network :

$$\text{Growth associated production :} \quad S + N + C \xrightarrow{\frown} X + P_1 \tag{2}$$

$$\text{Non} - \text{growth associated production :} \quad S + C + X \longrightarrow X + P_1 \tag{3}$$

where S, C, N, X and P_1 represent the carbon source, the oxygen, the nitrogen, the biomass and the PHB, respectively. In the first reaction scheme, the feedback arrow means that, in a growth reaction, the biomass is an autocatalyst. The presence of X on both sides of the arrow in the second reaction scheme means that X simply plays the role of a catalyst. The dynamical equations of the PHB process can be written in the above matrix form (in which $\Delta Q_{O2} = Q_{in} - Q_{out}$) :

$$\frac{d}{dt}\begin{pmatrix} S \\ C \\ N \\ X \\ P_1 \end{pmatrix} = -D\begin{pmatrix} S \\ C \\ N \\ X \\ P_1 \end{pmatrix} + \begin{pmatrix} DS_{in} \\ \Delta Q_{02} \\ DN_{in} \\ 0 \\ 0 \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} -k_1 & -k_2 \\ -k_3 & -k_4 \\ -k_5 & 0 \\ 1 & 0 \\ k_6 & 1 \end{pmatrix}\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} \tag{4}$$

where S_{in} and N_{in} the influent carbon source and nitrogen concentrations (g/l), Q_{in} and Q_{out} the inlet and outlet gaseous oxygen flowrates (g/h), r_1 and r_2 the reaction rates of the reactions (2) and (3) (h^{-1}) respectively and k_i (i = 1 to 8) the yield coefficients.

2.2 Example #2 : Anaerobic Digestion

Anaerobic digestion is a biological wastewater treatment process which produces methane. Four metabolic paths can be identified in this process : two for acidogenesis and two for methanization. In the first acidogenic path (Path 1), glucose is decomposed into fatty volatile acids (acetate, propionate), hydrogen and inorganic carbon by acidogenic

bacteria. In the second acidogenic path (Path 2), OHPA (Obligate Hydrogen Producing Acetogens) decompose propionate into acetate, hydrogen and inorganic carbon. In a first methanization path (Path 3), acetate is transformed into methane and inorganic carbon by acetoclastic methanogenic bacteria, while in the second methanization path (Path 4), hydrogen combines with inorganic carbon to produce methane under the action of hydrogenophilic methanogenic bacteria. The process can then be described by the following reaction network :

$$S_1 \longrightarrow X_1 + S_2 + S_3 + S_4 - S_5 \tag{5}$$
$$S_2 \longrightarrow X_2 + S_3 + S_4 + S_5 \tag{6}$$
$$S_3 \longrightarrow X_3 + S_5 + P_1 \tag{7}$$
$$S_4 + S_5 \longrightarrow X_4 + P_1 \tag{8}$$

where S_1, S_2, S_3, S_4, S_5, X_1, X_2, X_3, X_4 and P_1 are respectively glucose, propionate, acetate, hydrogen, inorganic carbon, acidogenic bacteria, OHPA (Obligate Hydrogen Producing Acetogens), acetoclastic methanogenic bacteria, hydrogenophilic methanogenic bacteria and methane. The dynamical model of the anaerobic digestion process ($N = 10, M = 4$) in a stirred tank reactor can be described within the above formalism (1) by using the following definitions :

$$\xi = \begin{pmatrix} X_1 \\ S_1 \\ X_2 \\ S_2 \\ X_3 \\ S_3 \\ X_4 \\ S_4 \\ S_5 \\ P_1 \end{pmatrix}, \; K = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -k_{21} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ k_{41} & -k_{42} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ k_{61} & k_{62} & 0 & -k_{63} \\ 0 & 0 & 0 & 1 \\ k_{81} & k_{82} & 0 & -k_{84} \\ k_{91} & k_{92} & k_{93} & -k_{94} \\ 0 & 0 & k_{03} & k_{04} \end{bmatrix}, \; F = \begin{pmatrix} 0 \\ DS_{in} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \; Q = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ Q_1 \\ Q_2 \\ Q_3 \end{pmatrix} \tag{9}$$

$$r = \begin{pmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{pmatrix} = \begin{pmatrix} \mu_1 X_1 \\ \mu_2 X_2 \\ \mu_3 X_3 \\ \mu_4 X_4 \end{pmatrix} \tag{10}$$

where μ_1, μ_2, μ_3, μ_4 are the specific growth rates (h^{-1}) of reactions (5), (6), (7), (8), respectively, and S_{in}, Q_1, Q_2 and Q_3 represent respectively the influent glucose concentration (g/l) and the gaseous outflow rates of H_2, CO_2 and CH_4 (g/l.h).

3 Model Order Reduction

Model simplification can be achieved by using the singular perturbation technique, which is a technique for transforming a set of $n+m$ differential equations into a set of n differential equations and a set of m algebraic equations. Consider that, for some i, the dynamics of the component ξ_i are to be neglected. The simplification is then achieved by setting ξ_i and $d\xi_i/dt$ to zero. It has been shown that the model order reduction rule is valid for low solubility productsand for bioprocesses with fast and slow reactions : in the latter case,