TECHNOLOGY DIFFUSION AND FORECASTING: THE CASE OF COMPUTATIONAL FLUID DYNAMICS (CFD) FOR SIMULATION OF GREENHOUSE INTERNAL ENVIRONMENTS.

L. PRETORIUS

Department of Engineering and Technology Management, Graduate School of Technology Management , University of Pretoria , South Africa.
leon.pretorius@up.ac.za

S KRUGER

Department of Mechanical Engineering Science, University of Johannesburg,, South Africa.
skruger@uj.ac.za

SJ BENADE

Department of Engineering and Technology Management, Graduate School of Technology Management , University of Pretoria , South Africa.
siebert.benade@up.ac.za

Received (Day Month Year)
Revised (Day Month Year)

Abstract - Forecasting emerging technologies as well the rate of diffusion of resultant products are complex in the context of management of technology usually because of a lack of relevant data. Techniques such as bibliometric analysis and the Bass diffusion model are utilized in this paper to assess the growth rate and market penetration of Computational Fluid Dynamics (CFD) as a technology. The penetration and growth rate of user acceptance of two CFD codes (not identified) are simulated. Furthermore a technology forecasting model of research and innovation in the field of application of CFD in the assessment of greenhouses is presented. Some CFD results of simulations for internal and external flow in an eight span greenhouse are presented as illustration of the power of CFD as technology

Keywords: CFD, Bass diffusion model, bibliometric analysis, management of technology, greenhouse, flow fields.

.

1 Introduction

Technology can be considered as the stock or inventory of knowledge, competencies and capacities that a firm has to compete effectively in the market place [Dorf and Byers, (2008); Nieto, (2004)]. Technology therefore forms part of the technology innovation process. In this sense innovation (management) is more of a rate dependant entity whereas technology is a level or stock quantity. Technology is both an input as well as an output of the innovation process [Nieto, (2004)]

Drejer [1997] takes a tool, system and value view on technology. The system view implies for instance that a user will be influenced by the technology. The value perspective of technology can on the other hand imply usefulness of a technology.

Drejer [1997] quotes Badaway that "*management of technology links engineering, science, and management disciplines to plan, develop, and implement technological* *capabilities to shape and accomplish the strategic and operational objectives of an organisation*." This definition of technology management places for instance research technology and product development in direct relation to the marketing and human resources functions in the firm. It is also implied that innovation can be considered a driver in the process of management of technology.

Fluid Dynamics and Heat Transfer are both natural phenomena that impact heavily on the engineering development and fundamental operation of many new product developments such as greenhouses for agricultural applications [Kruger and Pretorius, (2007)], photovoltaic solar water pumps [Van der Merwe, (2002)] , dry cooled condensers [Van Staden *et al*. (1998)] etc.

The innovation process of such new thermal equipment is directly influenced by the capability to do effective thermodynamic and fluid dynamic design. The Navier Stokes equations are generally utilized to model such physical phenomena. These equations are generally nonlinear partial differential equations and analytic solutions are not easy to obtain [Incropera and De Witt , (2006); Versteeg and Malalasekera, (2007)].

These equations can be discretized and form the basis of CFD to obtain approximate solutions to more general flow and heat transfer situations [Versteeg and Malalasekera, (2007)].

In the light of the aforementioned CFD as a body of knowledge used to effect a competitive position for a firm may be considered to be a technology and managed as a technology as part of the innovation process.

It is mentioned by Bae *et al.* [2007] that Bibliometric analysis can be usefully employed to gauge technology maturity. It is expected that in a technology growth phase the number of academic articles in the specific field of technology should also increase. This forms the basis of Bibliometric analysis. The results of these analyses may also be effective in assessing technology trends [Bae *et al.* (2007); Nieto, (2004)].

The application of Scientometrics to assess the extent of nanoscale research in South Africa is illustrated by Pouris [2007]. He uses this field of study related to Bibliometrics to discuss trends in nanoscale research in South Africa (SA) in relation to the international context. The study is intended to influence national policy of SA on nanoscale technology.

The process of adoption of technology and products by a potential market is under certain circumstances described by a diffusion model . One of the earlier models used for this diffusion process is the Bass diffusion model [Bass, (2004)].

A combination of Bibliometrics and the earlier Bass diffusion model is used in this paper to show trends in CFD technology development that can be used by executive management to assess their approach to technology management. This is also illustrated for the case of CFD simulation of the internal environment of an eight span greenhouse.

This article is an extension and contextualization of work presented in papers at ICMIT08 and ASME08 by the authors [Pretorius *et al.* (2008); Kruger and Pretorius, (2008)].

2 Methodology and literature review

2.1 *Bibliometric analysis*

It is mentioned by Bae *et al*. [2007] that Bibliometrics is essentially a process of measuring text and information. It can be used to appreciate some events that occurred in the past or even attempt to make some technology forecasts.

Jordan [2007] specifically mentions the use of Bibliometrics to trace technological change in his study of laptop battery future. The usefulness of this technique is illustrated by Jordan when he uncovers typical S-curves for Li-ion and lead acid batteries that indicate saturation for these technologies from the databases . He interprets this as that a breakthrough for a new technology may be impending.

In this paper the technology trend for Computational Fluid Dynamics (CFD) as a technology is traced via Bibliometrics. The main data source used is Google Scholar [2008]. This may be limiting on the research but will be addressed in future research.

2.2 *Bass diffusion model*

The discrete equivalent of the basic Bass diffusion model is described by the following equation [Bass, (2004); Mahajan *et al.* (1995); Bass curves, (2008)] :

$$\mathrm{N}_t = \mathrm{N}_{t-1} + p\left(m - \mathrm{N}_{t-1}\right) + q\frac{\mathrm{N}_{t-1}}{m}\left(m - \mathrm{N}_{t-1}\right) \tag{1}$$

The symbols in Eq. (1) have the following meaning:

N_t : number at time t
p : coefficient of innovation or external influence
q : coefficient of imitation or internal influence
m : total market size

Further versions of the generalized Bass Diffusion model are also available [Mahajan *et al.* (1995); Danaher *et al.* (2001)] . In these versions the effect of substitution is also considered. In this paper the aim is first only to show that CFD as a technology also has some saturation characteristics and that the Bass diffusion model may be employed to assess some trends. The effect of substitution and cross pollination between technologies and eg second generations is not considered explicitly in the numerical model. The diffusion of CFD technology in greenhouse applications is also explored.

The coefficient of innovation is typically indicative of the adopter's action to the product mainly because of the perceived new benefits whereas the coefficient of imitation indicates a pressure on the adopter because the product seems to belong to a usual set that he has to have.

2.3 *CFD technology*

In Computational Fluid Dynamics a numerical solution of a set of partial differential equations, typically the Navier-Stokes equations are obtained [Incropera and De Witt , (2006); Versteeg and Malalasekera, (2007)]. These partial differential equations govern the transport of mass, momentum and energy in moving fluids [Versteeg and Malalasekera, (2007)]. The laws governing the transport of the above quantities are: conservation of mass, Newton's second law of motion and the first law of thermodynamics [Van Staden *et al*. (1998)]. Finite volume discretization is the first step in solving these transport equations.

In this method the solution domain is subdivided into a finite number of small control volumes, that correspond to the cells of a computational grid. Discrete versions of the integral form of the continuum transport equations are applied to each volume. The objective of this method is to obtain a set of algebraic equations. An algebraic multi-grid solver can then be used to solve the resulting algebraic equations. [StarCCM+, (2006)]. The transport of a simple scalar is considered as illustration. The continuous integral form of the governing equation is typically given by [StarCCM+, (2006)]:

$$\frac{d}{dt}\int_V \rho\phi dV + \oint_A \rho\phi\left(\bar{v} - \bar{v}_g\right)\cdot d\bar{a} = \oint_A \Gamma\nabla\phi \cdot d\bar{a} + \int_V S_\phi dV \qquad (2)$$

Where $\rho =$ density

$\phi =$ scalar quantity

V = cell volume

$\bar{v} =$ velocity

$\bar{v}_g =$ grid velocity

$\Gamma =$ diffusion coefficient

$\bar{a} =$ face area vector

$S_\phi =$ Source Term

The first term in Eq. (2) is the transient term, the second term is the convective flux, the third term the diffusive flux, and the last one the volumetric source term. The mathematical formulation of each term is also typically defined in the StarCCM+ documentation [StarCCM+, (2006)]. When Eq. (2) is discretized, the following equation results that can be implemented in CFD simulation software :

$$\frac{d}{dt}\left(\rho\phi V\right)_0 + \sum_f \left[\rho\phi\left(\bar{v}\cdot\bar{a} - G\right)\right]_f = \sum_f \left(\Gamma\nabla\phi\cdot\bar{a}\right)_f + \left(S_\phi V\right)_0 \qquad (3)$$

Where G = grid flux computed from mesh motion

A more detailed description of a discretization procedure can be found in Patankar [1980] In order to include buoyancy source terms in the momentum equation, the gravity model can be activated in the resulting CFD simulation software. To approximate the buoyancy source term, the Boussinesq model has been implemented for the current greenhouse case by selecting a constant density flow. The Boussinesq model is described by:

$$f_g = \rho\bar{g}\beta\left(T_{ref} - T\right) \qquad (4)$$

Where :

$\bar{g}$ = gravitational vector

$\beta =$ Coefficient of Bulk Expansion

$T_{ref} =$ Operating Temperature.

3 Model and results

3.1 *CFD technology trends*

To compare the currently developed Bass model by the authors using Eq. (1) as a basis for a spreadsheet application the data presented by Shang *et al.* [2004] for Personal Computer (PC) demand were fitted to a Bass curve by means of optimisation of the Bass diffusion parameters m (total market size), p (coefficient of innovation) and q (coefficient of imitation). Data for PC demand correlate to a number of months reported on in 1988.

This Bass model used is an original version of the model introduced my Bass [2004].It is adapted for numerical solution in a spreadsheet application. There are further versions of the Bass model available including for instance the effect of marketing [Mahajan *et al.* (1995); Danaher *et al.* (2001)].

The optimized parameters obtained by the author with Excel's solver [Gotfried, (2007)] are shown in Table 1. It should be evident that the current model produces similar values to that suggested by Shang *et al*. [2004]for the specific PC market data considered. The simulated value of 1793*100 for eventual demand (eventual potential market segment size) compares well with the value of 1800*100 produced by Shang *et al*. [2004].

Table 1 Optimised diffusion parameters for pc demand

		M	P	Q
Current model		1793.028	0.035295	0.190435
Previous data []		1800.32	0.035	0.188

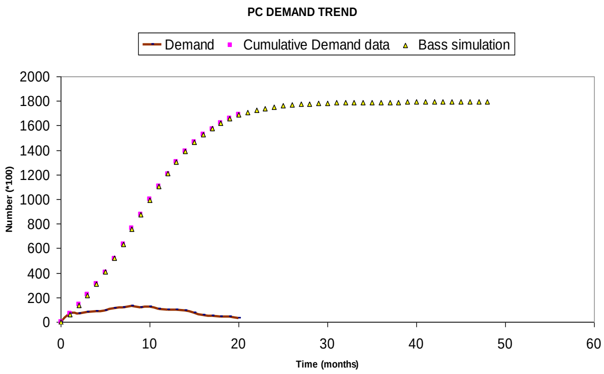

Fig. 1. Demand Trend for PC's compared with Shang *et al.* [2004]

It is therefore assumed that the basic Bass diffusion model utilized in the current computer simulation will suffice for the intended purpose of at least qualitative exploratory forecasting and trend assessment. It is however also appreciated that some of the PC demand data supplied may have been infected with resale data which according to [Shang *et al).* (2004] may corrupt the simulation. The trend is however considered to be in order for the current trend analysis purpose.

Having established the appropriateness of the current model for at least some available PC data some confidence exists in the model developed by the authors and it is deemed fit to proceed in applying the model to the case of CFD technology. PC as a hardware technology has in this section also been shown to have diffusion and saturation characteristics. Many software CFD codes as technologies are currently also available for use on certain PC's. It is thus deemed appropriate to examine the diffusion characteristics of CFD technology.

The Bibliometric data used to assess the Bass curve shown in Fig.2 for the CFD technology trend are derived from research articles in Google Scholar [2008] with words for example 'CFD Technology, year A to year B'. In this process the time of near zero publications is determined iteratively in Google Scholar. Thereafter the number of appropriate articles are determined cumulatively from the start date for the applicable technology.

The optimized Bass diffusion parameters obtained with Excel's solver are shown in Table 2. It should be evident that the current model is in good agreement with data for the first 30 years of the CFD technology development. The technology is still far from maturity as indicated by the relatively large value of 28676 articles for M. The Q value of 0.322 is in the range suggested by previous literature [Shang *et al.* (2004); Bass, (2004)].

Year zero data correlate to 1976 data. What is also interesting to note is that Bibliometrics may be used to establish in some sense even the inception of a technology such as CFD.

Table 2 Optimised diffusion parameters for cfd technology trend

		M	P	Q
CFD technology		28676.69	3.59787E-05	0.322255

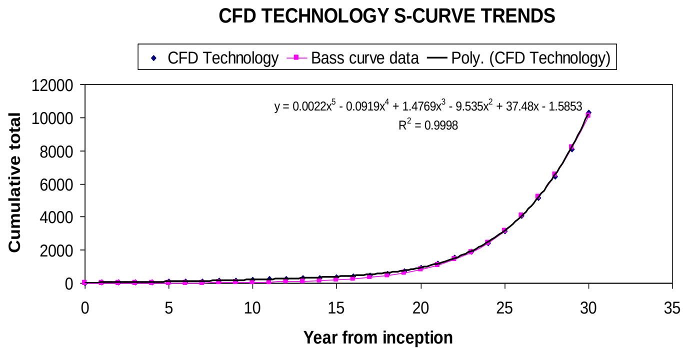

Fig. 2. Technology trend for CFD

3.2 *CFD research trends for greenhouses*

To illustrate the power of this CFD technology excerpts of simulation results obtained for a eight span greenhouse by the authors [Kruger and Pretorius, (2008)] are presented.

Table 3 summarizes the temperatures and velocities used for the wall boundaries of the greenhouse in the numerical model CFD, while Table 4 is a summary of the properties used in the k-epsilon turbulence flow model.

Table 3: Boundary conditions used in CFD model similar to [Ould *et al.* (2006)]

PARAMETERS	VALUES
Inlet Air	
Velocity at 6m [m/s]	**1.4**
Temperature [°C]	**22.2**
Temperature [°C]	
Outside Air	22.2
Outside Ground	27.9
Inside Ground	27.3
Roof	33.6
Plastic Central Partition	31.3
Glass Walls	29.1

Table 4: K-epsilon turbulence model parameters used

Under Relaxation Factor	0.8
Convergence Tolerance	0.1
Epsilon	0.0
Turbulent Viscosity (Under Relaxation Factor)	1.0

The power of CFD to simulate flow and temperature conditions inside the greenhouse for design purposes should be evident from figures 3 and 4. The existence of recirculation flow fields with inside velocities of 0.1 – 0.2 m/s due to the external flow as well as buoyancy inside in especially the first and second span is amply and visually illustrated using CFD as technology.

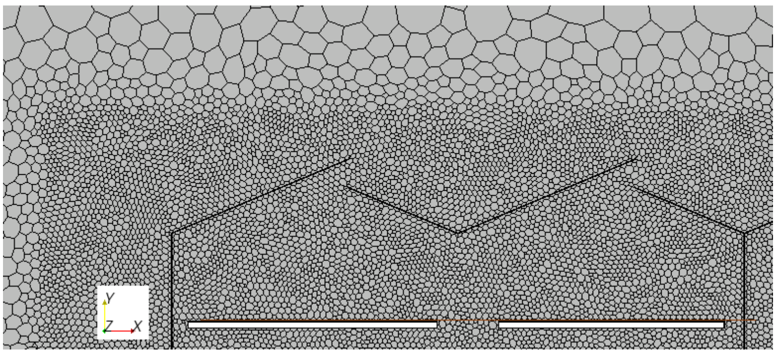

Fig. 3**:** Refined Polyhedral Discretized Mesh around the Greenhouse

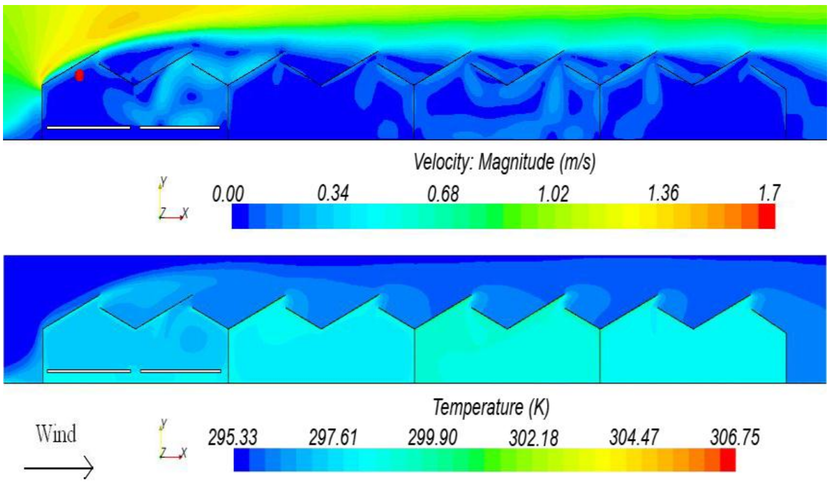

Fig. 4: Velocity and Temperature Contour Plots

The question is now to what extent CFD has diffused into the greenhouse applications area. Delving further into the technology of CFD development this case of application of CFD to greenhouse environment simulation is assessed via Bibliometric data for CFD in greenhouses from year 1998.

The Bibliometric data used to simulate the Bass curves shown in Fig.3 are derived from research articles in Google Scholar [2008] with words for example 'CFD Greenhouse, year A to year B'.

The optimised Bass curve for a fit of all the available data to year 9 is shown in Fig.5. If only Bibliometric data up to year 8 are used to fit a Bass curve it can be shown that the prediction is 6.77% in error at time 9.

With the full set of data a saturation value of 982 units is predicted with the Bass model. If only data up to time 8 are used the predicted M value can be shown to be approximately 824 units 16.05% below the 982 target.

This may indicate that care should be taken with predictions far into the future with the current Bass model for CFD in greenhouses. What is however evident is the usefulness in assessing CFD technology trends, also for greenhouse applications. As Bouwman *et al.* (2003) state it "scenario development starts where technology forecasting ends" [Bouwman and Van der Duin, (2003)]. This focuses the attention on the uncertainty aspect of forecasting illustrated in the previous illustration. The forecasts made eg for CFD technology in greenhouses may be usefully seen as starting points for trends and scenarios that may develop from that point onward.

Table 5 Optimised diffusion parameters for CFD greenhouse technology trend

		M	P	Q
CFD greenhouse		982.1213	0.025056	0.451653

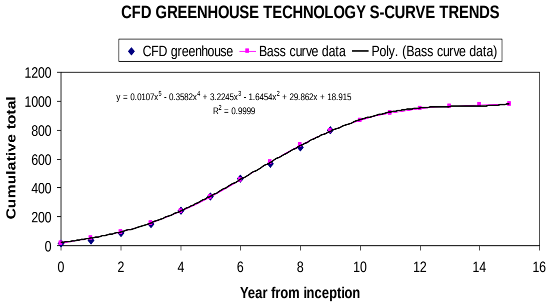

Fig. 5. Technology trend for CFD for greenhouse applications

3.3 *Trend for CFD software products*

These CFD simulations of the flow environments for the greenhouse may be achieved using different CFD software codes. These codes may be own in house developed codes or commercially available codes. The current flexibility and extensive development effort that have been put into commercial codes seem to favour the use of commercial codes.

The development trends for two CFD software products (the results of CFD technology) are now traced via Bibliometrics and simulated with the numerical Bass model to illustrate the extensive market penetration of as well as difference between two of these CFD codes..

The Bibliometric data used to assess the Bass curves shown in Fig.6 and Fig.7 are derived from research articles in Google Scholar [2008] with words for example 'CFD Code A , year A to year B'.

From Table 6 it may be inferred that research done with Code A may peak somewhat earlier than with Code B but with a steeper growth pattern. This may be due to the fact that Code A was introduced somewhat later than Code B. The maximum value should not be stressed too much in this case as the initial data obtained are scarce and not as reliable. What should however be evident from Fig. 6 and Fig. 7 is the quite different curve forms for Codes A and B also a result of the diffusion parameters shown in Table 6 . A competitive pattern of behaviour may even be postulated from the difference in curve appearance for Codes A and B.

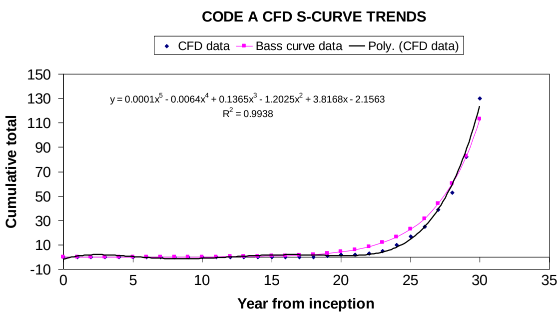

Fig. 6. Technology trend for CFD Code A

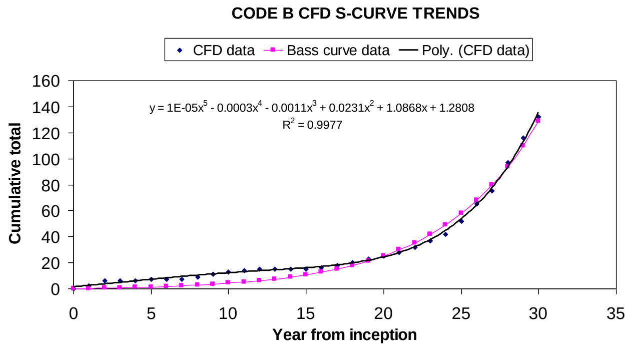

Fig. 7. Technology trend for CFD Code B

Table 6 Optimised diffusion parameters for code a and code b

	M	P	Q
Code A	920.8454	2.26E-06	0.399259
Code B	2661.74	6.83E-05	0.176473

4 Discussion

From Fig.2 through Fig.5 it should be evident that it is possible to construct S-curves using the Bass model that can effectively emulate or forecast observed cumulative publication data on CFD technology and CFD technology also in greenhouse applications. The observation is that the numerical and discretized version of the Bass model is appropriate over the time span involved.

A note of care should however be sounded when too much emphasis is placed on absolute values of forecasts. There is uncertainty in data obtained as well as range of forecasts as have been shown for the greenhouse applications. This is where it is useful rather to think in terms of trends and scenarios as also emphasized by Bouwman and Van der Duin [2003].

All the forecasting and subsequent analyses have assumed availability of information in the "market" [Bass, (2004)] as well as no repeat buys. The effect of the introduction of one technology on another has thus not been addressed in the simulations.

It is very useful to be able to at least recognize the existence of a mature level, M of a technology at some point in the future . This is effectively illustrated in Fig. 5 where CFD in greenhouse simulation seems to approach some mature limit level that may indicate immanence of transfer to another or derivative technology as also referred to by Bae *et al.* [2007]. The full field of CFD technology applications does not seem near saturation as indicated by Fig. 2.

All of these forecasts and trend casts for CFD technology have been made possible through the optimized regression of Bibliometric data for CFD and the Bass diffusion model. This was done by the author making use of the nonlinear solver in a spread sheet application [Gottfried, (2007)].

A trend cast is also added as a trend line y=f(x) on the appropriate graphs in Fig.2 through Fig.7 . As an example the trend for the cumulative CFD technology "adoptors" (publications) y as a function of year x shows a CFD technology trend :

$$y = 0.002151x^5 - 0.091948x^4 + 1.476946x^3 - 9.535003x^2 + 37.479869x - 1.585270$$
$$R^2 = 0.999819 \qquad (2)$$

Care should however be exercised in using these fifth order polynomials to forecast more than one or two time increments into the future as explained previously for the Bass equation. It can be shown that these fifth order polynomials can proceed to negative unrealistic cumulative future values under certain circumstances.

5 Conclusion

This paper focused on the forecasting of CFD technology. It was shown that technology forecasting is possible for CFD although the issue is probably more trend casting than forecasting.

The Bass diffusion model was identified as a useful modeling vehicle for the CFD technology considered across the indicated time spans. Care should be taken not to forecast more than one or two time units into the future at which time more data should be available and the current optimized Bass model can be updated for the CFD technology considered and further forecasting attempted.

The application of CFD in the greenhouse was explored. It was demonstrated that circulatory flow patterns existed especially in the first two spans of the greenhouse considered. The use of CFD as technology to analyse the environment inside a greenhouse has been effectively demonstrated. The diffusion of CFD technology in the context of analysis of greenhouse environments was specifically evaluated.

Future research may include the effect of one technology or derivative thereof on another technology applied to for instance the increased use of CFD for design applications in greenhouse design. The generalized Bass model or other models focusing on inclusion of competition (in the form of competing technologies) as well as the effects of geographical location may be studied for this application. Furthermore alternative diffusion models such as Logistic/Pearl or the Gompertz models may also be studied for this CFD technology as indicated by Crompton [2001] in his study on the diffusion of new steelmaking technology.

References

1. Bae, J. Seetharaman, K. Suntharasaj, P. and Ding Y. (2007). Technology forecasting of RFID by using bibliometric analysis and Bass diffusion model. *Proc. PICMET 2007*, 1637-1642, Portland , Oregon, USA, 5-9 August.
2. Bass curves for the diffusion of innovation, (2008). http://www.useit.com/alertbox/basscurves.html , accessed 17/03/2008
3. Bass, F.M. (2004). A new product growth model for consumer durables. *Management Science*, **50**, 12: 1825-1832, December .
4. Bouwman H. and van der Duin, P. (2003). Technological forecasting and scenarios matter. *Foresight*, **5**, 4.
5. Crompton, P. (2001). The diffusion of new steelmaking technology. *Resources Policy*, **27**: 87-95.

6. Danaher, P.J. Hardie, B.G.S. and Putsis Jr, W.P. (2001). Marketing mix variables and the diffusion of successive generations of technological innovation. *Journal of Marketing Research* , **38**, 4: 501-514, November.
7. Dorf, R.C. and Byers, T.H. (2008). *Technology ventures from idea to enterprise*. McGraw-Hill, New York.
8. Drejer, A. (1997). The discipline of management of technology based on considerations related to technology. *Technovation*, **17**, 5: 253-265.
9. Google Scholar (Beta), (2008). http://scholar.google.co.za/, accessed 17/03/2008.
10. Gottfried, B.S. (2007). *Spreadsheet tools for engineers using Excel*. McGraw-Hill, New York.
11. Incropera F.P. and De Witt, D.P. (2006). *Fundamentals of Heat and Mass Transfer*. Wiley.
12. Jordan, S.W. (2007). Technology forecasting with science indicators: the case of laptop battery futures. *Proc. PICMET 2007*":1643-1650, Portland , Oregon, USA, 5-9 August.
13. Kruger S. and Pretorius, L. (2007). The Effect of Ventilator Configurations In Naturally Ventilated Greenhouse Applications ," *Proceedings ,UK National Heat Transfer Conference* , Edinburgh, 10-11 September.
14. Kruger, S. Pretorius, L. (2008). Comparison Of The Indoor Climate In Multi-Span And Detached Greenhouses With Various Ventilator Configurations. *Proc. ASME International Mechanical Engineering Congress and Exposition*, November 2-6, Boston, Massachusetts, USA.
15. Mahajan, V. Muller E. and Bass, F.M. (1995). Diffusion of new products: empirical generalizations and managerial uses. *Management Science,* **14**, 3, part 2 of 2: G78-G88.
16. Nieto, M. (2004). Basic propositions for the study of the technological innovation process in the firm. *European Journal of Innovation Management*, **7,** 4: 314-324.
17. Ould Khaoua, S.A. Bournet, P.E. Migeon, C. Boulard T. Chassériaux. (2006). Analysis of greenhouse Ventilation Efficiency based on Computational Fluid Dynamics, *Biosystems Engineering*. **95**, 1: 83-98.
18. Patankar, S.V. (1980) *Numerical Heat Transfer and Fluid Flow*. Washington: Hemisphere.
19. Pouris, A. (2007). Nanoscale research in South Africa :A mapping exercise based on scientometrics. *Scientometrics*, **70**, 3: 541-553.
20. Pretorius, L. Benade, S. Kruger, S. (2008). Technology Forecasting: The Case of Computational Fluid Dynamics (CFD). *Proc. 4th IEEE International Conference on Management of Innovation and Technology*, 21 – 24 September , Bangkok, Thailand
21. Shang, J.S. Li S. and Tadikamalla, P. (2004). Operational design of a supply chain design system using the Taguchi method, response surface methodology, simulation and optimization. *Int. J. Prod. Res.*, **42**, 18: 3823-3849, 15 September.
22. StarCCM+ , (2006). *CFD Manuals*, CD-Adapco.
23. Van der Merwe, L. (2002). *A product development process for a photovoltaic water pump system in a small to medium enterprise,* doctoral thesis , Rand Afrikaans University, South Africa.
24. Van Staden, M.P. Pretorius L. and Meyer, J.P. (1998). Simulation of heat exchange in large air cooled condensers. *Proc. of the 11th International Heat Transfer Conference*, **6**:155-160, Kyongju, Korea, 23-28 August.
25. Versteeg, H.K.and Malalasekera, W. (2007). *An introduction to Computational Fluid Dynamics: the Finite-Volume Method*. 2nd Edition, Pearson, ISBN 978-0-13-127498-3.