

# Modeling and Control of an Internal Bubble Cooling System

D. Belloli, S. M. Savaresi  
Dip. di Elettronica e Informazione  
Politecnico di Milano  
via G. Ponzio, 34/5 – 20133 Milano, Italy

A. Cogni, F. Previdi  
Dip. di Ingegneria dell'Informazione e Metodi Matematici  
Università degli Studi di Bergamo  
via Marconi, 5 – 24044 Dalmine (BG), Italy

D. Cazzola  
Dip. di Ricerca e Sviluppo  
Doteco S.p.A.  
via E. Mattei, 30 – 40137 San Martino Spino (MO), Italy

**Abstract**— In this paper, the modeling and the control design problems for a Internal Bubble Cooling (IBC) system are considered. A dynamic model has been developed using a physical approach and validated with experimental measurement. The model has been used to design the closed-loop control architecture to regulated the bubble diameter. The controller has been tuned by simulation and its effectiveness has been verified with experimental tests.

**Keywords:** *plastic film process; internal bubble cooling; modeling; control*

## I. INTRODUCTION

Internal bubble cooling (IBC) systems are key elements in the plastic film process, which has a standard setup including a dosing section, a bubble forming extruder and a film rolling part.

The different plastic components, in form of solid granulate, pellets or bits, are properly dosed and mixed with particular mechatronic systems, like as gravimetric feeder [14,15]. The mix of solid plastic materials is warmed by a series of electrical heaters, obtaining a uniform melt of polymer. The material is pushed towards a die and blown with fresh air, forming a “bubble” (see Fig. 1). Then a mechanical cage equipped with moving rollers compresses and transforms the bubble in a plastic film which is wrapped on bobbins.

During the process, the physical properties of the final produced film are strictly related to complex thermo-mechanical transformations of the polymer in the bubble forming section [4,5,9,13,17]. The desired chemical properties are achieved regulating the air thermal exchange in the bubble, which also affects the width of resulting film in according with the cage and rollers constraints.

Traditionally the IBC systems are manually regulated: an expert operator sets the proper air flows in the bubble and the cage width in order to obtain the required plastic film.



Figure 1. Internal Bubble Cooling (IBC) system.

In this paper, the control design problem for a IBC system is considered. Specifically, a closed-loop architecture has been used to regulated the bubble diameter. The control algorithm is based on a PID (Proportional, Integral, Derivate) structure, which parameters have been tuned on the basis of the IBC model. The physical approach has been applied to describe single components and the different equations have been joined in a complete model afterwards. The model validation has been performed comparing the simulation results with experimental measurements.

The paper is organized as follows. In Section II, the experimental equipment is illustrated and the control problems are defined. In Section III, the model of the system and the control structure are described in Section III and Section IV respectively. Section V is devoted to concluding remarks.

## II. PROBLEM STATEMENT AND EXPERIMENTAL SETUP

The mechanical layout of the IBC system used in the present work is shown in Fig. 2. The melt of polymer (produced by the extruder) is passed through a die, which converts it in a semi-solid plastic tube.

A cold air flow, coming from inner vents, blows the plastic tube toward the top, which assumes the form of a bubble. In order to maintain constant and stable the bubble volume, the warm air is removed by a pipe placed in the middle of the die. The two air flows (fresh and warm) are generated by external blowers and on the exhaust line an electro-pneumatic valve is mounted to modulate the warm air flow. In order to bound its diameter, the bubble is canalized by a moving cage driven by electrical motor and equipped with gap sensors. In the upper part of the structure, an absolute diameter sensor is installed before the bubble is crushed by circular rolls and converted in film form, which is wrapped on bobbins.

In order to control the bubble diameter, several actuators are available. The blowers, responsible of the inflation of the bubble, are manually set by an operator who fix the speeds of the electrical motors connected to fan to obtain the proper air flows needed for a medium diameter in stability condition. The accurate regulation of the bubble width is demanded to the electro-pneumatic valve on the exhaust pipe. In this device, a pneumatic cylinder drives a stem connected to the circular shutter which modulates the cross section area (see Fig. 3): changing the stem position is possible to control the warm air flow coming out and therefore the bubble diameter.



Figure 3. Electro-Pneumatic Valve.

In addition to the air flow, it is necessary to regulate the moving cage driven by a step motor. The cage width has to be set in according with the bubble dimension: with a large cage, the bubble can move and oscillate compromising the quality of the plastic film; otherwise a narrow cage is very critical because of the risk of holes forming responsible of bubble deflation and collapse. Then the control strategy has to coordinate the outgoing air flow, operating on the electro-pneumatic valve, and the cage width, acting on the step motor.

To design an accurate control strategy, the bubble sensors have to be considered. Typically in the IBC system there are two different transducers: the gap sensor mounted on the bottom of the cage and the diameter sensor installed on the top of the structure. The first one provides the distance between the bubble and the moving cage, where the device consisting in three optic units placed at  $120^\circ$  shift is mounted on. This information is fundamental to avoid the holes forming and deflation of the bubble. Moreover this sensor measures the instant bubble dimension variation because of its position in the bottom part of the cage and close to the die. Nevertheless the produced signal is quite inexact and affected by noise due to fact that in the initial part of the bubble the thermal process of the plastic material solidification is not completed yet. The accurate information of the bubble width comes from the diameter sensor placed on the top of the structure where the plastic material is completely stable. However this transducer is affected by a substantial delay due to the transportation time that the plastic material take to move from the die to the sensor.

Summarizing, the control strategy has to regulate the bubble diameter acting on the air flow and the cage position, driven by the valve and step motor respectively, on the basis of the dynamic information of the gap sensor and the accurate steady-state measurement of the diameter transducer.

## III. MODELING OF IBC SYSTEM

In order to the understand the relationship between the actuators [8] (electro-pneumatic valve and step motor of the cage) and available measurements (bubble diameter and gap distance), a dynamic model of the IBC system has been developed. The behaviors of the most significative components of the plant will be analyzed and the physical equations will be joined to obtain the complete model [6,10,11].

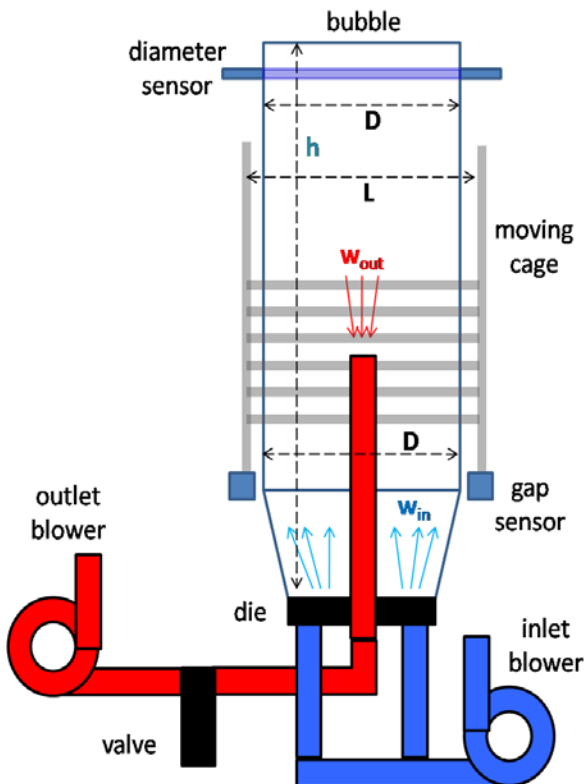


Figure 2. Diagram of IBC system.

The most important part of the system is the bubble dynamic: the bubble volume  $V(t)$  is defined by

$$V(t) = \frac{\pi h}{4} \cdot D^2(t) \quad (1)$$

where  $D(t)$  is the bubble diameter and  $h$  is the bubble height (considered constant as imposed by the plant dimension). Considering the conservation equation referred to the air mass in the bubble, the volume variation can be obtained as

$$\frac{dV(t)}{dt} = \frac{\pi h}{4} \cdot 2D(t) \cdot \frac{dD(t)}{dt} = w_{IN} - w_{OUT}(t) \quad (2)$$

where  $w_{IN}(t)$  and  $w_{OUT}(t)$  are the inner and outer air flows respectively.

In this operating conditions, the inner air flow is supposed constant because it results from the blower speed set by the operator and maintained fixed. Because of the identical drive structure, the outer air flow depends on the fixed outer blower speed and, differently from the inner flow, from the valve opening. The outer flow  $w_{OUT}(t)$  results proportional to the cross section area of the valve  $x_V(t)$  modulated by a circular shutter driven by the valve stem, through the valve gain  $\mathcal{G}_V$

$$w_{OUT}(t) = \mathcal{G}_V \cdot x_V(t) \quad (3)$$

The bubble diameter is measured by an accurate sensor placed at the top of the cage: considering the material transport delay  $\tau$ , the diameter measurement  $D_M(t)$  can be described as

$$D_M(t + \tau) = D(t) \quad (4)$$

The bubble volume is also conditioned by the cage width, which is regulated by a step motor. Due to the particular drive structure, the electric motor can be moved only at fixed speed: then the cage can be enlarged or narrowed, in according with the direction of the motor speed, or maintained constant when the motor is not activated. The entity of the cage width variations depend on the duration of the speed command provided to the motors. Then the dynamic behavior of the cage width, which represents the maximum diameter achievable by the bubble, can be summarize with

$$\frac{dL(t)}{dt} = \mathcal{G}_C \cdot \omega_{COM}(t) \quad (5)$$

where  $L(t)$  is the cage width,  $\omega_{COM}(t)$  the step motor command and  $\mathcal{G}_C$  the cage gain.

The distance between the cage and the bubble is measured by three optical sensors. The gap  $g(t)$ , based on the bubble and cage radius, can be calculated as

$$g(t) = \frac{L(t) - D(t)}{2} \quad (6)$$

The physical equations that describe the dynamic behavior of the main part of the plant have been joined to obtain the complete model of the IBC system:

$$\begin{cases} \frac{dD(t)}{dt} = \frac{1}{D(t)} \cdot \frac{2}{\pi h} \cdot (w_{IN} - \mathcal{G}_V \cdot x_V(t)) \\ \frac{dL(t)}{dt} = \mathcal{G}_C \cdot \omega_{COM}(t) \\ D_M(t + \tau) = D(t) \\ g(t) = \frac{L(t) - D(t)}{2} \end{cases} \quad (7)$$

The IBC system can be represented as a MIMO II order model. The two dynamics variable are the bubble diameter and the cage width, forced by the electro-pneumatic valve and the step motor speed of the moving cage. The available measurement are the delayed bubble diameter and the gap distance. It is worth to underline the presence of the non-linear behavior, due to the diameter dependence in the differential equation of the bubble diameter, and the material transport delay, which have to be considered to design the proper control strategy.

The differential equations of IBC model have been converted from the time domain to the frequency domain through the Laplace Transform and joined in the scheme shown in Fig. 4.

The model parameters have identified using an experimental data set in order to minimize the error between simulation and measurements with the non-linear least squares method [1,16]. The resulting parameters are reported in Table 1.

TABLE I. MODEL PARAMETERS VALUE

Parameters	Unit	Value
$\mathcal{G}_V$	$\frac{m^3}{s} / \%$	$2.7671 \cdot 10^{-4}$
$w_{IN}$	$\frac{m^3}{s}$	$2.0794 \cdot 10^{-2}$
$\mathcal{G}_C$	$\frac{mm}{s} / bit$	80
$\tau$	$s$	11.73

The IBC model has been validated (see Fig. 5) comparing the experimental data (blue line) with the simulation results (red line). A different dynamic test has been considered, where the two inputs (valve opening and cage motor command) are set to obtain proper diameter and gap variations.

The main dynamics of the IBC system are correctly described by the model, especially for the gap distance, and also the steady state value are sufficiently accurate.

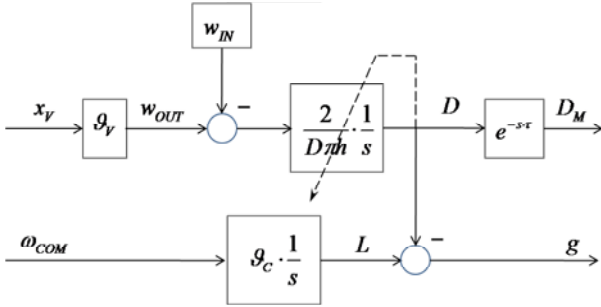


Figure 4. Diagram of IBC model.

#### IV. CONTROL STRATEGY OF IBC SYSTEM

The IBC system presents two inputs and two outputs (MIMO), so it is possible to define two targets to achieve with the control structure [2,3]. The main important variable to regulate is the bubble diameter but the dimensional constraint due to cage width must also be considered: for this reason, the gap distance between the bubble and the cage is regulated to avoid the formation of holes in the bubble and its consequent deflation.

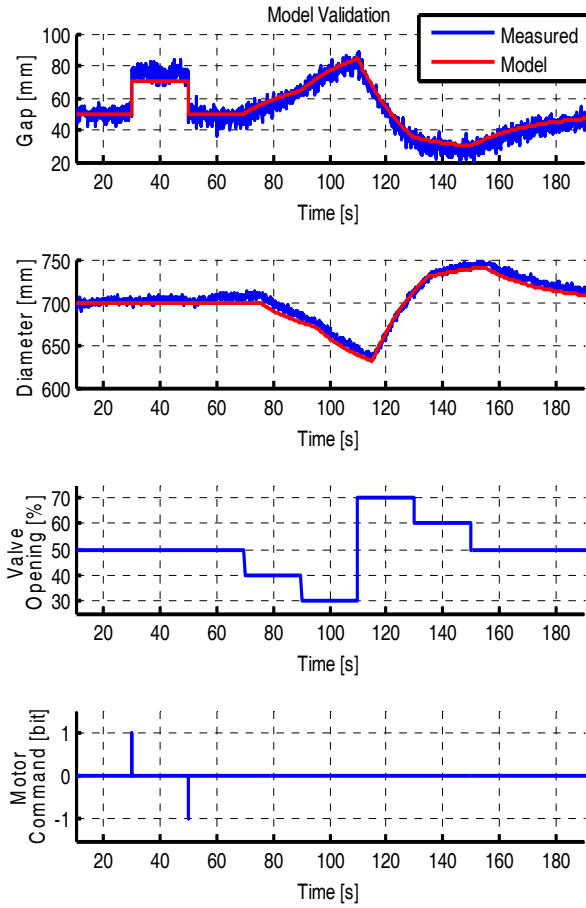


Figure 5. IBC model validation.

Initially it is necessary to decide the coupling of measurements and control variables in the control architecture. Analyzing the relationships in the model, it has been noted that the diameter depends only from the valve opening input whereas the gap is related to both the inputs variables. Then the most reasonable architecture suggests to regulate the bubble diameter with the valve opening and the gap distance with the cage motor. This solution has been tested but it resulted not proper for this application because of the long settling time of the bubble diameter and the nervous behavior of the gap distance. The first phenomenon is due to the consistent delay of the diameter measurement, which can vary from a minimum of 8s to 20s in according with the line velocity. The gap behavior is caused by the step motor that moves the cage: the electric drive does not allow to modulate the motor speed, which can assume just the maximum value in both the direction or the null value. Considering also the high sensitivity of the cage width variations to the motor speed due to mechanical cinematic, a small command to the step motor determines excessive variation of the cage width, preventing an accurate control of the gap distance.

For these reasons the other possible control strategy has been applied (see Fig. 6): the valve opening is commanded to maintain constant the gap distance between cage and bubble and the step motor is activated to move the cage and to obtain the desired bubble diameter. This control strategy is focused on the gap controller: the more accurate and fast is the gap control loop, the more performing is the regulation of the bubble diameter. This hypothesis is reasonable because the gap sensors provide an instant and precise measure while the valve can be carefully modulated.

In order to control the gap distance, a PID regulator [7,12,18] has been designed: the proportional and integral gains has been tuned on the basis of the IBC model to guarantee to clear the steady state error between the constant reference and gap measurement and to obtain the widest bandwidth. In the implementation of the PI the anti wind-up strategy has been used to avoid the control variable saturation for excessive periods.

Since the gap distance is properly regulated, the target diameter is achieved moving the cage with small step generated by the motor. Due to the limitations of the electrical drive (which can only active the motor at constant speed), the control strategy has to generate a discrete command to the motor on the base of the plant condition.

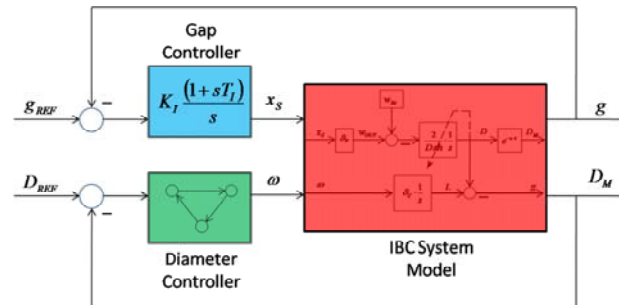


Figure 6. Scheme of IBC control structure.

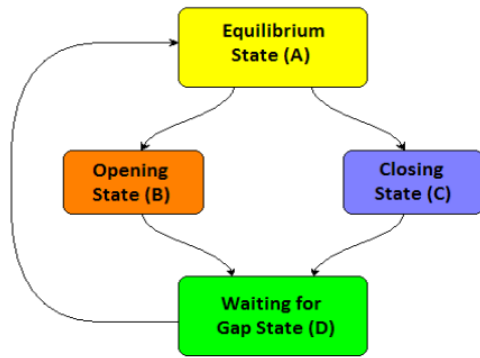


Figure 7. Scheme of the discrete-event machine of the diameter controller.

This idea has been implemented with a discrete-event machine, composed by different states and transition conditions (see Fig.7). When the gap distance and the bubble diameter both are close to the respective set-points, the system is at the equilibrium state (A) and no motor command and cage movement are required. Otherwise, when the diameter is different from the target for a long time, the step motor has to be activated in order to enlarge or narrow the cage, which correspond to opening (B) and closing (C) state respectively. Moving the cage, a variation of the gap occurs: in this situation, which corresponds to the last state (D), the motor cage is disabled to let the gap controller bring the gap distance back to the target.

The proposed control strategy, composed by a PID regulator for the gap distance and discrete-event machine for the bubble diameter, has been implemented and tested on the real plant.

The experimental results shown in Fig. 8 confirm the effectiveness of the proposed control strategy. The gap distance is maintained close to set-point of 50mm: the maximum error is 20mm and results lower than desired tolerance (40mm). It is worth to note that the gap never reach the zero value, that means that the bubble does not bump against the cage. The bubble diameter assumes the correct value imposed by the reference: the steady state value is accurate and the transient time is about 7s.

## V. CONCLUSION AND FUTURW WORKS

In this paper, a dynamical model and a control architecture for IBC system has been developed. The model, based on a physical approach, has been tuned considering experimental measurement and its accuracy has been validated with different data. The model has been used to develop the control strategy, which consists in a PI regulator for the gap distance and discrete-event logic for bubble diameter. The proposed control algorithms have been successfully applied to the real plant.

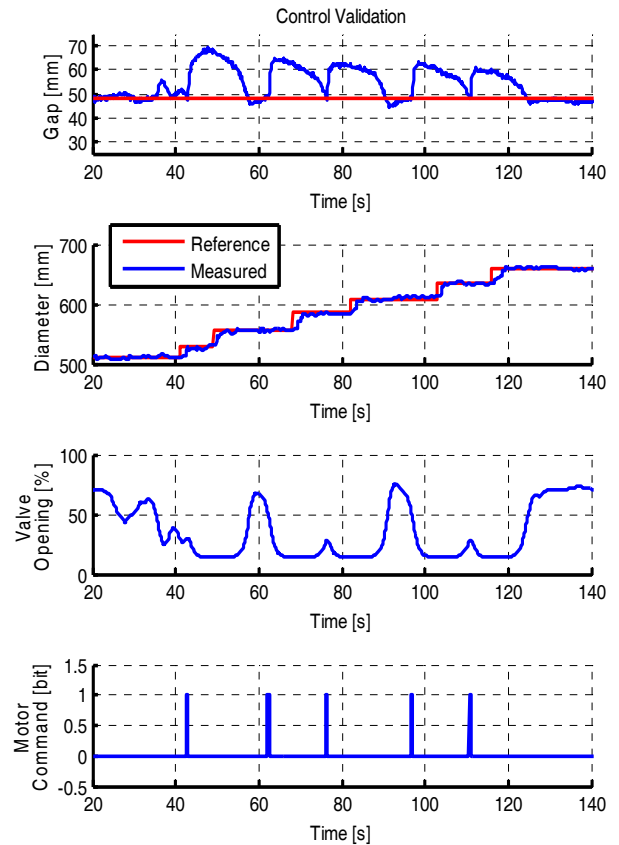


Figure 8. IBC control validation.

In future works more details will be considered and more advanced control algorithm will be applied. In particular the gain scheduling control will be examined to adapt the control strategy to gain system variations due to non-linearity introduced by the diameter. Moreover a delay compensation will be considered to contain the effect of the material transport delay in the bubble diameter measurement.

Finally the hypothesis of mechanical layout changing is under investigation. In particular, a study on a new valve is in progress in order to reduce the losses and obtain a more efficient and accurate modulation of section area. Besides the direct air flow control is under analysis despite it requires the addition of flowmeter sensors and the possibility to modulate the blower speed.

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