

DISSERTATION

On

**Bond Graph Aided Hydraulic Flow Model of Plant in Response to
Physical and Environmental Factors**

Submitted in partial fulfillment of the requirement for the award of degree

of

Master of Engineering

IN

CAD/CAM Engineering

Submitted by

Bhrigu Kumar Lahkar

Roll No.: 801481006

Under the guidance of

Dr. TARUN KUMAR BERA

Associate Professor

Department of Mechanical Engineering

Thapar University, Patiala



DEPARTMENT OF MECHANICAL ENGINEERING

THAPAR UNIVERSITY

PATIALA-147004, INDIA

JULY-2016

DECLARATION

I hereby declare that work done in the thesis report entitled, "Bond Graph Aided Hydraulic Flow Model of Plant in Response to Physical and Environmental Factors" submitted towards partial fulfillment of requirement for award of Master of Engineering degree in CAD/CAM Engineering in Mechanical Engineering Department of Thapar University, Patiala, is an authentic record of work carried out by me under the supervision and guidance of Dr. Tarun Kumar Bera, Associate Professor of Mechanical Engineering Department, Thapar University, Patiala.

Date: 15/07/16

Bhriku Kumar Lahkar

Bhriku Kumar Lahkar

This is to certify that above declaration made by the student concerned is correct to the best of my knowledge and belief.

Tarun Kumar Bera 15/7/16

Dr. Tarun Kumar Bera

Associate Professor

Mechanical Engineering Department

Thapar University, Patiala

Countersigned by:

SSS
Head of Mechanical Engineering Department
Thapar University, Patiala

Abhinaly
Dean of Academic Affairs
Thapar University, Patiala

ACKNOWLEDGEMENT

I would like to express my profound exaltation and gratitude to my supervisor Dr. Tarun Kumar Bera, Associate Professor, Mechanical Engineering Department, Thapar University, Patiala for his candid guidance, constructive propositions and overwhelming inspiration in the nurturing work. It has been a blessing for me to spend many opportune moments under the guidance of the perfectionist at the pinnacle of professionalism. The present work is testimony to his activity, inspiration and ardent personal interest, taken by him during the course of his work in its present form.

I am grateful to Dr. S. K. Mohapatra, Sr. Professor and Head, Mechanical Engineering Department for providing facilities in successful completion of this work.

Finally, I would like to express my sincere gratitude to all who directly or indirectly helped me to complete my thesis report.



Bhriku K Lahkar

Roll No.: 801481006

ABSTRACT

With the increase of imbalance in ecosystem and natural chaos researchers have been putting focused effort in evaluating the behavior of biological plant communities in response to various environmental and physical factors. Therefore, understanding of water transport in soil–plant–atmosphere continuum is essential for the management of ecosystem. The first objective of this present research is to get a comprehensive picture of the physical principles behind transportation of water from soil to roots and then in the plant up to the aerial parts. The work is inter-disciplinary in nature. From the physical principles, a mechanical model for a simplified plant consisting of one root, a stem and a big leaf that deals with the water dynamics of vegetation is derived. This mechanical model is put into bond graph notation which deals with the water dynamics within the plant, called the hydraulic flow model. The hydraulic flow model is a mechanistic model based upon plant physiological behavior which is used to study functionality of different plant organs in handling water flow. Different resistance elements are introduced into the model corresponding to various sections of the plant out of which stem xylem resistance and stomatal resistance are modeled. Stem xylem resistance is modeled by taking diurnal change of stem xylem diameter into account. The resistance model of stomata is developed with the help of Jarvis-Stewart model for stomatal resistance. The process of transpiration is also incorporated into the model which is developed with the help of Ohm's law analogy. Thermal behavior of the vegetation is introduced by taking boundary layer, aerodynamics, ambient temperature, relative humidity and global solar radiation into account. Calculations are mostly done for specific kind of plants and for specific sight. Finally, various environmental and physical influencing factors are considered to study the response of the model which offers novel modeling tactics alternative to the field measurements.

Keywords: Biological plant, Hydraulic flow model, Water potential, Transpiration, Physical and environmental factors, Bond graph

NOMENCLATURE

A_s	Stem cross-sectional area
C_p	Specific heat of air at constant pressure
c	Molar concentration
D	Diffusivity
e_a	Water vapor pressure of ambient air
e_s	Water vapor pressure of ambient air at saturated condition
g	Acceleration due to gravity
h_p	Plant height
L_I	Leaf Area Index (LAI)
R	Universal gas constant
R_H	Relative humidity of ambient air
R_G	Global solar radiation
$r_{s(\min)}$	Minimum stomatal resistance
S_d	Slope of saturated vapor pressure versus temperature curve
u	Wind speed
V_d	Vapor Pressure Deficit (VPD)
\dot{V}_t	Transpirational flow rate
Δx_s	Stem length
λ	Latent heat of evaporation for water
ρ_s	Hydraulic resistivity of stem
ψ	Water potential

SUBSCRIPTS

a	Aerodynamic
b	Boundary layer
e	Electrical
l	Leaf
ls	Leaf storage
p	Hydrostatic
rx	Root xylem
S	Soil
s	Stomata
ss	Stem storage
sx	Stem xylem
v	Vein
π	Osmosis

LIST OF FIGURES

Figure No.	Figure Caption	Page No.
1.1	Bond graph representation of resistive element	5
1.2	Bond graph representation of compliance element	5
1.3	Bond graph representation of inertial element	6
1.4	Bond graph notation of source of effort element	6
1.5	Bond graph representation of source of flow element	7
1.6	Bond graph representation of transformer element	7
1.7	Bond graph representation of gyrator element	8
1.8	(a) LCR in parallel	8
	(b) Bond graph representation	8
1.9	(a) LCR in series	9
	(b) Bond graph representation	9
2.1	(a) Schema of soil-plant system	12
	(b) Electrical analogy of steady state model	12
3.1	(a) Hydraulic architecture of the simple plant	17
	(b) Mechanical equivalence	17
3.2	Bond graph model of a simple plant	18
3.3	Variation of soil water potential during 5 days	19
3.4	(a) Diurnal change in stem diameter for a single day	20
	(b) Change in stem xylem resistance for a period of 5 days	20
3.5	(a) Incoming solar radiation	23
	(b) ambient temperature and relative humidity of air for 5 days	23
3.6	Schema of transpiration process from stomata to atmosphere	24

3.7	Effect of constant and variable soil water potential on	
	(a) Transpirational flow rate	28
	(b) Flow rate into and out of leaf storage element	28
	(c) Flow rate from stem xylem to leaf	28
	(d) Flow rate into and out of stem storage element	28
3.8	Effect of constant and variable soil water potential on	
	(a) Water potential at root cross-section	29
	(b) Stem water potential	29
	(c) Leaf water potential	29
	(d) Water potential comparison at each compartment of plant	29
3.9	Daily changes of stomatal resistance in response to constant and variable soil water potential	30
4.1	Schema of leaf energy balance	31
4.2	(a) Effect of various factors on stomatal resistance	33
	(b) Solar radiation (day 1)	33
4.3	Effects of constant and variable solar radiation on	
	(a) Transpiration	34
	(b) Flow rate into and out of leaf storage element	34
	(c) Flow rate from stem xylem to leaf	34
	(d) Flow rate into and out of stem storage element	34
4.4	Effects of constant and variable solar radiation on	
	(a) Water potential at root cross-section	35
	(b) Stem water potential	35
	(c) Leaf water potential	35
4.5	Schematic representation of aerodynamic resistance on plant	36

4.6	Effect of plant height on	
	(a) Transpiration	37
	(b) Flow rate into and out of leaf storage element	37
	(c) Flow rate from stem xylem to leaf	37
	(d) Flow rate into and out of stem storage element	37
4.7	Effect plant height on	
	(a) Water potential at root cross-section	38
	(b) Stem water potential	38
	(c) Leaf water potential	38

LIST OF TABLES

Table No.	Table Caption	Page No.
1.1	Flow and effort variables in various energy domains	4
3.1	Values of various parameters	26

TABLE OF CONTENTS

DECLARATION	ii
ACKNOWLEDGEMENT	iii
ABSTRACT	iv
NOMENCLATURE	v
SUBSCRIPTS	vi
LIST OF FIGURES	vii–ix
LIST OF TABLES	x
CHAPTER 1: INTRODUCTION	1–10
1.1 Background and motivation	1
1.2 Plant water dynamics	1–3
1.2.1 Osmotic potential	2
1.2.2 Gravitational potential	2
1.2.3 Hydrostatic potential	2–3
1.2.4 Capillary action	3
1.2.5 Diffusion	3
1.3 Research methodology	3–4
1.4 Bond graph modeling	4–9
1.4.1 Basic single port elements	5–7
1.4.2 Basic two port elements	7–8
1.4.3 Junction elements	8–9
1.5 Scope and contribution of the thesis	9–10
1.6 Organization of the thesis	10
CHAPTER 2: LITERATURE REVIEW	11–15
2.1 Literature review on plant water dynamics	11–14
2.2 Bond graph in plant physiology	14
2.3 Literature gap	14
2.4 Objective of present research	15

CHAPTER 3: EFFECT OF SOIL WATER POTENTIAL	16–30
ON PLANT FUNCTIONALITIES	
3.1 Hydraulic flow model of a simple plant	16–19
3.1.1 Mechanical equivalence of a simple plant	16
3.1.2 Bond graph model of simple plant	16–19
3.2 Influencing parameters of hydraulic flow model	19–23
3.2.1 Soil water potential	19
3.2.2 Stem xylem resistance	20
3.2.3 Leaf resistance	21–23
3.3 Modeling of transpiration	23–25
3.4 Simulation results	26–30
CHAPTER 4: EFFECT OF SOLAR RADIATION AND PLANT HEIGHT	30–38
ON PLANT FUNCTIONALITIES	
4.1 Leaf energy balance	31–32
4.2 Influence of various environmental factors on stomatal resistance	32–33
4.3 Simulation results of solar radiation effect	33–35
4.3.1 Effect of solar radiation on volume flow rates	33–34
4.3.2 Effect of solar radiation on water potentials	35
4.4 Effect of plant height on various factors	35–36
4.5 Simulation results of plant height effect	36–38
4.5.1 Effect of plant height on volume flow rates	37
4.5.2 Effect of plant height on water potentials	38
CHAPTER 5: CONCLUSIONS	39–40
5.1 Conclusions	39
5.2 Future scope of model development	40
REFERENCES	41-43
CURRICULUM VITAE	44

Hydraulic flow model of biological plant affects water transportation process from roots to leaves and hence, different models have different consequences. As all the mechanisms responsible for water movement in plants are yet to be explored, therefore, to determine the advantages and disadvantages of a specific model is quite hypothetical. However, study of such models is rewarding, as it can provide insights for predicting the behavior of plants in response to different environmental changes.

1.1 Background and Motivation

Over a few decades, investigations on different plant species have been deepening with an aim to improve the basic understandings of fundamental mechanisms behind water absorption from soil. Therefore, to look at the plants' behavior as a whole, study of hydraulic flow model of plant is essential and has been studied since long time.

Study of hydraulic flow models of plants is advantageous as it provides information on various relevant questions on plant physiology i.e.

- 1) At the time of continuously decreasing soil water content, how do the trees program themselves to survive by transpiring less?
- 2) How do the trees use stored water for survival strategy during the critical time of depleted soil water content?
- 3) How do various functionalities of a plant change with the change of plant height?

Therefore, knowing the answers to these questions can enable us to efficiently predict the behavior of plants with respect to the climatic changes. In past decades, different flow models based upon electrical analogy are described by considering steady state process. Though significant advancement in model development has been achieved in past, there is still ample scope to develop a mechanistic model for transient water uptake. Therefore, prime motivation for developing an integrated flow model and solving it computationally is that it can allow assessment of physiological characteristics which are generally very difficult to measure. It can also serve as an efficient alternative model which will be able to dictate the fundamental mechanisms of plant water dynamics.

1.2 Plant Water Dynamics

Under natural conditions plant water uptake is a transient flow process controlled by various influencing factors such as soil hydraulics, plant configuration, climatic conditions etc. Therefore to develop model for water movement through plant requires understanding of

water dynamics in main compartments of a plant. Plant water dynamics is a superposed concept of various mechanisms, where the driving force required for movement of water from soil to atmosphere is difference in water potential.

Water potential (ψ) is the most commonly measure of water status in plants which indicates amount of available energy per unit volume to induce sap flow. It is defined as the summation of osmotic (ψ_{π}), hydrostatic (ψ_p), gravitational (ψ_g) and electrical potential (ψ_e).

$$\psi = \psi_{\pi} + \psi_p + \psi_g + \psi_e \quad (1.1)$$

1.2.1 Osmotic potential (ψ_{π})

Osmotic potential is defined as the potential required preventing water flow from a region of lower to higher solute concentration through a differentially semipermeable membrane separating the two solutions. It is colligative property which depends upon number of solute particles present in the solution. For dilute solutions, osmotic potential can be expressed in terms of solute concentration and this is given by Van't Hoff's law as

$$\psi_{\pi} = -cRT, \quad (1.2)$$

where c is the summation of all solute species molar concentrations (molL^{-1}), R is the universal gas constant ($8.3 \text{ Jmol}^{-1}\text{K}^{-1}$) and T is absolute temperature (K).

1.2.2 Gravitational potential (ψ_g)

It is nothing but the pressure required to transport water from a reference surface (usually soil surface) to a height h .

$$\psi_g = \rho gh_p, \quad (1.3)$$

where ρ (kgm^{-3}) is water density, g (9.8 ms^{-2}) is gravitational acceleration and h_p (m) is height of plant (relative to a reference surface).

1.2.3 Hydrostatic potential (ψ_p)

Hydrostatic potential is also termed as pressure potential which is the effect of hydrostatic pressure that the free energy of water experiences. Positive pressure increases the water potential; negative pressure reduces it. The positive pressure which occurs in the living cells of plant is referred to as *turgor pressure* which is responsible for growth and cell metabolism. However, negative pressure generally occurs in the xylem conduits are referred to as *tension* which arises due to capillary effect.

Since, pure water or dilute solution is electrically neutral, therefore electrical potential is neglected. Again osmotic potential is neglected by assuming that for long distance transport osmotic potential changes are not important. Similarly, gravitational potential is not considered for simplicity of the model. Hence, hydrostatic potential is the dominant part which is responsible for the transportation of water through the xylem vessels and from the soil to root. Water potential by convention is considered as negative and its value is zero in case of pure water at atmospheric pressure. Other important phenomena which contribute to the flow of water are capillary rise and diffusion.

1.2.4 Capillary action

It is the phenomenon of rise or fall of liquid in a narrow bore capillary tube relative to general and adjacent level of liquid. This property depends upon forces of cohesion and adhesion. Due to the cohesive force in the solution, water is continuously pulled up in the capillary as water rises along its walls. The water will stop to rise the moment the adhesive force and the gravitational force of the water column has come to an equilibrium point.

1.2.5 Diffusion

Diffusion is defined as the motion of molecules from a higher concentration region to a region of lower concentration. It can be formulated by Fick's law of diffusion which is an empirical approach that states that the mass flow rate of a species is proportional to the concentration gradient and a diffusion coefficient.

$$J = -D \frac{\partial \phi}{\partial z}, \quad (1.4)$$

where J = diffusion flux rate (mol/m²s)
 D = diffusivity (m²/s)
 ϕ = concentration (amount of substance per unit volume) (mol/m³)
 z = length (m)

1.3 Research Methodology

In the present work, an integrated hydraulic flow model is developed establishing a mechanistic linkage between physical phenomenon and mechanical equivalent elements. The model assigns springs with different stiffness and dampers that deals with water dynamics within the plant. This model is then put into a structured graphical notation called *bond graph* and then simulated to evaluate various functionalities of the plant with respect to various environmental and physical influencing factors. Modeling and simulation work is done with the *Symbol-Shakti* software. The bond graph model can easily handle large number of system

equations and constraints. Implementation of bond graph also allows usage of unified representation across all energy domains with only seven basic elements. In addition, bond graph facilitates direct physical interpretation for different segments of a plant. These advantages justify the implementation of bond graph technique in the current research.

1.4 Bond Graph Modeling

Bond graph is a graphical formalism which considers exchange of power between two subsystems of a system, process or phenomena under observation. It is a powerful tool where different energy domains can be represented (e.g. electrical, mechanical, hydraulic, thermal etc.) in a system without losing its topology. This revolutionary idea was originated by Prof. H.M. Paynter in 1959 in which systems are portrayed by power bonds connecting junctions, elements of a physical system. Flow of bi-directional information (flow and effort) between junctions is the unique characteristic of Bond graph lexicon which is decided by the causal strokes. Bond Graph introduces seven basic standard elements– inertial (I), compliance (C), dissipater (R), source of effort (Se), source of flow (Sf), transformer (TF) and gyrator (GY). Using these elements any types of system can be modeled and hence, it is called as a unified approach. To create a bond graph model of any type of physical system one should recognize the effort and flow variable first. Then, it is required to find out the compartments between which power flows. Finally, to distinguish all the elements or subsystems which describe the observed system completely. Parameters representing flow and effort variables in different systems of different energy domain are tabulated below.

Table 1.1 Flow and effort variables in various energy domains (Mukherjee et al., 2006)

Systems	Effort (e)	Flow (f)
Mechanical	Force	Velocity
	Torque	Angular velocity
Electrical	Voltage	Current
Thermal	Temperature	Entropy flow rate
	Pressure	Volume flow rate
Hydraulic	Pressure	Volume flow rate
Chemical	Chemical potential	Molar flow rate
	Enthalpy	Mass flow rate
Magnetic	Magneto-motive force	Magnetic flux

1.4.1 Basic single port elements

Single port elements are elements which are addressed with a single power bond where a single pair of flow and effort variable exists at the port. There are five single port elements out of which three are passive elements (I, R and C) and other two are active elements (SE and SF). These elements are described below

- Resistive element: It is denoted by ‘R’ in bond graph. For different energy domains the resistive elements are analogous to each other. A dashpot or damper in mechanical system, an electrical resistor in electrical domain and porous plugs in fluid transmission line are considered as resistive elements. The causality of the resistive elements may be either inductive or resistive depending upon the system. It is graphically represented by

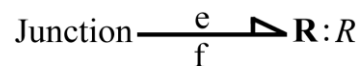


Fig. 1.1 Bond graph representation of resistive element

$$F = R.\dot{x} \quad (1.5)$$

$$e = R.f \quad (1.6)$$

From equation (1.5) and (1.6) an effort output from the resistive element can be observed, which signifies resistive causality in the junction side.

- Compliance element: It is an energy storing element which is represented by ‘C’ in bond graph notation. It establishes an algebraic relation between effort and generalized displacement. It also relates effort to the time integral of flow. In mechanical domain a spring or torsion bar, in electrical system a capacitor and in a hydraulic system an accumulator is considered as compliance elements. In bond graph notation for a mechanical spring of stiffness k it can be graphically shown by

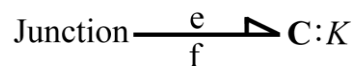


Fig. 1.2 Bond graph representation of compliance element

$$F = k.x \quad (1.7)$$

$$e = k.Q \quad (1.8)$$

$$e = k \int_{-\infty}^t f(t)dt \quad (1.9)$$

Equation (1.8) and (1.9) shows an integral causality where effort is the output from the element and flow is the input.

- Inertial element: It is an energy storing element denoted by ‘I’ in bond graph lexicon. It relates flow to the time integral of flow. It is generally used to represent inertial and inductance effects in mechanical and electrical systems respectively. Graphical representation of inertial element in case of a mechanical system with mass m can be shown as

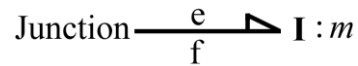


Fig. 1.3 Bond graph representation of inertial element

$$F = m \cdot \ddot{x} = m \frac{df}{dt} \quad (1.10)$$

$$f = \frac{1}{m} \int_{-\infty}^t e dt \quad (1.11)$$

Equation (1.10) and (1.11) shows integral causality of the inertial element with effort as the cause and flow as consequence.

- Source of effort: It is an active port which is represented by ‘SE’ character in bond graph. Here the half arrow always points away from the source symbol signifying power input to the remaining system in terms of external effort. In mechanical domain force or torque, in electrical domain electrical potential and in hydraulic system pressure is considered as source of effort. Specifically, in case of plant communities water potential is the essential source of effort for the movement of water flow. It is graphically represented as

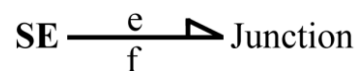


Fig. 1.4 Bond graph notation of source of effort element

- Source of flow: In bond graph technique it is represented by ‘SF’ character. Likewise, source of effort the half arrow always points away from the source symbol signifying power input to the remaining system in the form of flow. In mechanical domain displacement, in electrical domain electrical current and in hydraulic system volume flow rate is considered as source of flow. It is graphically represented as

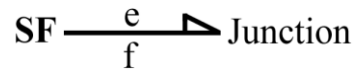


Fig. 1.5 Bond graph representation of source of flow element

1.4.2 Basic two port elements

These are the elements in which two bonds are connected to the element with two pairs of effort and flow associated with it. The two types of two port elements are ‘Transformer’ and ‘Gyrator’ and can be represented symbolically as ‘TF’ and ‘GY’ in bond graph notation.

- Transformer: It can be ideally represented by a massless rigid lever in mechanical system and by an electrical transformer in electrical domain. It neither creates nor destroys energy. It transforms one form of flow to the other in a different domain (e.g. velocity to volume flow rate in a piston-cylinder arrangement) or acts as a scalar multiplier which magnifies or reduces the amount of flow from one side of the system to the other. The multiplication factor is known as modulus (μ) of the transformer which is shown in Fig. 1.6. The curved arrow shown represents a sense of direction in which the modulus is to be used.



Fig. 1.6 Bond graph representation of transformer element

$$f_2 = \mu \cdot f_1 \quad (1.12)$$

$$e_2 \cdot \mu = e_1 \quad (1.13)$$

$$e_2 \cdot f_2 = e_1 \cdot f_1 \quad (1.14)$$

Equations (1.12) and (1.13) shows that transformer element acts as a converter that converts flow to flow and effort to effort. Equation (1.14) establishes conservation of power.

- Gyrator: The gyrator element acts as a converter which establishes a relationship between effort to flow and flow to effort (equation (1.15) and (1.16)). It is denoted by ‘GY’ in bond graph. An ideal representation of a gyrator element is a mechanical gyroscope in mechanical domain and a DC motor in an electrical system. It is graphically represented as

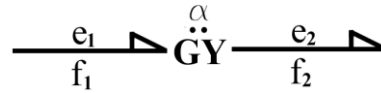


Fig. 1.7 Bond graph representation of gyrator element

$$e_2 = \alpha \cdot f_1 \quad (1.15)$$

$$e_1 = \alpha \cdot f_2 \quad (1.16)$$

$$e_2 \cdot f_2 = e_1 \cdot f_1 \quad (1.17)$$

Likewise transformer, it neither creates nor destroys energy and establishes a power conservation relationship as shown in equation (1.17).

1.4.3 Junction elements

There are two genders of junction elements, 0-junction and 1-junction. The no. of bonds connected to the junction element can be as many as possible depending upon the system. It distributes either flow or effort to other junctions or elements.

- 0-junction: It resembles Kirchoff's node law or the plumbing analogy where the flow leaves from the node or the junction must be equal to the amount of flow enters as long as there is no loss in between. The sign of the flows are determined by the half arrow direction. A 0-junction can be conveniently described by a passive LCR circuit in parallel connection (Fig. 1.8).

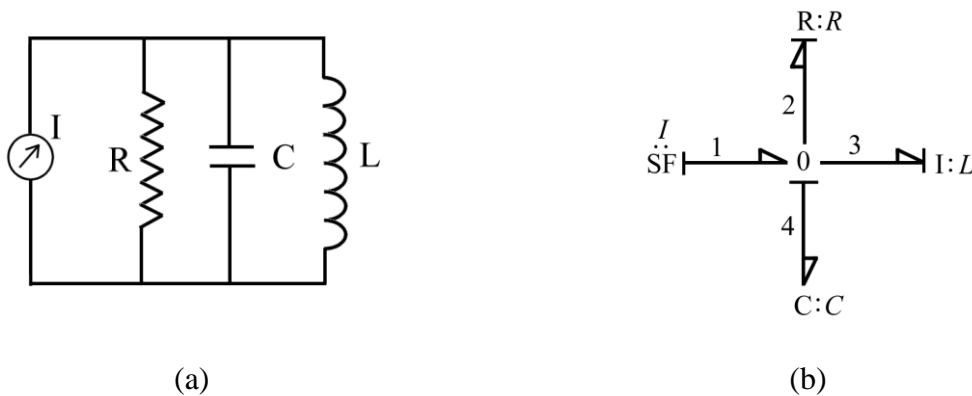


Fig. 1.8 (a) LCR in parallel with (b) bond graph representation

$$e_1 = e_2 = e_3 = e_4 \quad (1.18)$$

$$f_1 = f_2 + f_3 + f_4 \quad (1.19)$$

$$e_1 \cdot f_1 = e_2 \cdot f_2 + e_3 \cdot f_3 + e_4 \cdot f_4 \quad (1.20)$$

It is also governed by equality of effort rule or flow summation rule as depicted in equations (1.18) and (1.19). Equation (1.20) establishes power conservation principle.

- 1-junction: The law governing in 1-junction element is analogous to mesh law in electrical domain. Here total summation of efforts in the junction is equal to zero and have equality of flows. The sign of the flows are determined by the half arrow direction. A 1-junction can be conveniently described by a passive LCR circuit in series connection (Fig. 1.9).

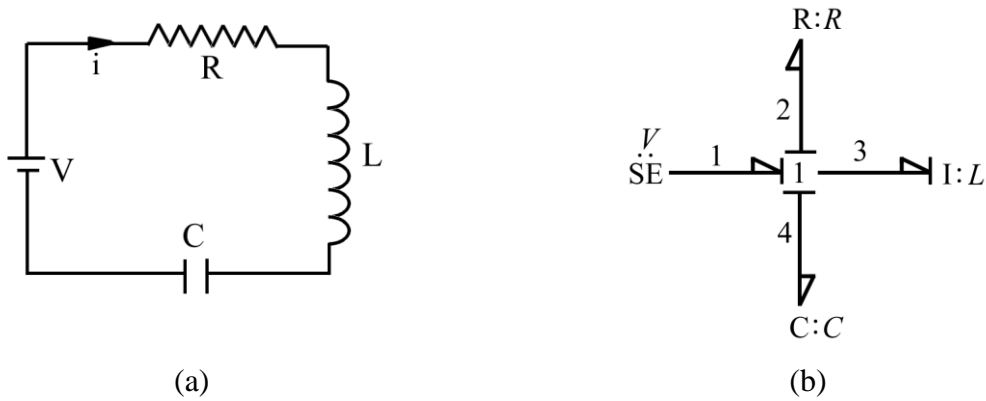


Fig. 1.9 (a) LCR in series with (b) bond graph representation

$$f_1 = f_2 = f_3 = f_4 \quad (1.21)$$

$$e_1 = e_2 + e_3 + e_4 \quad (1.22)$$

$$e_1 \cdot f_1 = e_2 \cdot f_2 + e_3 \cdot f_3 + e_4 \cdot f_4 \quad (1.23)$$

From equations (1.21) and (1.22) it can be observed that 1-junction is governed by equality of flows rule. It is also known as flow sum junction. Equation (1.23) establishes power conservation principle.

1.5 Scope and Contribution of the Thesis

Scope of the current research work mainly lies within the conventional modeling and simulation framework of bond graph tool. Though certain parameters of the hydraulic flow model could have been measured using experimental set up, but due to lack of time and lab facilities these are directly taken from published literature. Attempt has been made to take into account almost all possible factors that affect the hydraulic flow model. The noteworthy contributions of the present work are pointed out below.

- From the hydraulic architecture of a simple plant, a mechanical equivalence model is developed termed as hydraulic flow model
- The model is put into bond graph notation that deals with water dynamics within the plant

- Various mechanisms relating to plant water uptake phenomena are discussed in detail
- All the influencing parameters that affect the hydraulic flow model are described in detail
- Stem xylem resistance and leaf resistance are modeled by taking diurnal variations into account
- A model of transpiration is also developed with the help of Ohm's law analogy
- Various environmental and physical factors are introduced in the model to make it more realistic

1.6 Organization of the Thesis

The structure of the thesis is organized as follows

Chapter 1 contains introduction of various physical phenomena behind water uptake process that deals with plant water dynamics. Next basic idea of bond graph is presented which is used as a research methodological technique in the current thesis work. Various scopes as well as contributions are also discussed in this chapter which is essential for successful completion of the thesis.

Chapter 2 is pertaining to the literature study work. Extensive studies on various literatures are done mainly on two areas: (i) Plant water dynamics and (ii) Bond graph in plant physiology. Literature gap as well as objectives of the current research work is also discussed in the chapter.

Chapter 3 deals with effect of soil water potential on different plant functionalities. First the hydraulic architecture of a simple plant consisting of one root, a stem and a big leaf is modeled with sets of mechanical equivalent elements. Then, mechanical equivalent model is formulated in bond graph notation. In the next step, simulation results of the bond graph model in response to different soil water condition are discussed.

Chapter 4 deals with effect of solar radiation and plant height on different plant functionalities. First theoretical discussions related to incoming solar radiation, leaf energy budget and aerodynamic resistance are presented. Finally, simulations results are discussed in detail.

Chapter 5 is discussed with various conclusion remarks based upon the results presented in chapter 3 and chapter 4. Scope of future model development is also suggested at the end.

Literature study on numerous research papers and book chapters was carried out focusing mainly in two areas: (i) Plant water dynamics and (ii) Bond graph in plant physiology. Out of extensive study of various literatures, certain objectives were drawn that lies within the modeling and simulation framework of bond graph technique is also presented in the current chapter.

2.1 Literature Study on Plant Water Dynamics

Water uptake and transportation phenomenon in plants have been a key topic among researchers to determine behavior of plants in response to various environmental and physical factors. Under natural conditions, plant water uptake is a transient flow process controlled by various influencing factors such as soil hydraulics, plant configuration, climatic conditions *etc.* Therefore, developing model for water movement through plant requires understanding of water dynamics in main compartments of a plant. Xylem is a tissue which is mainly responsible for movement of water and nutrients from root compartment to leaf and other parts of organs. Though, transportation of water is a superposed phenomenon of various mechanisms, the most acceptable theory of water transport in plants is Cohesion-Tension Theory (**Dixon and Joly, 1895**). This theory states that water molecules inside the vessel elements are pulled upwards due to negative potential gradient along the length, strong cohesive force between water molecules and ability of water to stick against vessel walls due to adhesive force. Thus, due to tension between water molecules these form a water column inside. This causes the elastic walls of the vessel elements to bend inwards and diameter of the tree stem shrinks. This change in diameter of stem was investigated by **MacDougal (1924)** and later on by **Irvine and Grace (1997)** as a transpiration induced phenomenon. Diurnal change of stem diameter for peach trees due to variations of stem water content was observed by **Simonneau et al. (1993)**. Variation of water status within the plant is not the only reason for enlarging and shrinking of tree stem diameter, but also thermal expansion of tissues play an important role for changing trunk diameter (**Huguet, 1985**).

The driving force required for transportation of water from soil to atmosphere depends on the difference in water potential at the two ends along with a resistance between them (**Jarvis et al., 1981**). This is completely analogous to the flow of electricity through electrical resistance. This particular idea was first proposed by **Van den Honert (1948)** and later on

extensively used by **Cowan (1965)** in several models. Van den Honert used a *black box* resistance model in which steady flow rate of water can be calculated. It is defined as

$$\dot{V}(t) = \frac{\Psi_s - \Psi_l}{R_{s-l}}, \quad (2.1)$$

where $\dot{V}(t)$ is steady water flow rate of, Ψ_s and Ψ_l are water potentials at soil and leaf respectively and R_{s-l} is overall plant hydraulic resistance between soil and leaf (Fig. 2.1).

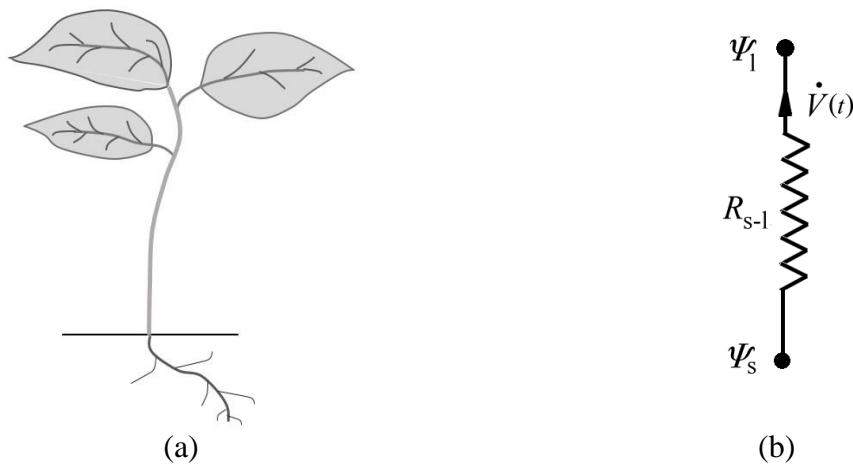


Fig. 2.1 (a) Schema of soil-plant system and (b) electrical analogy of steady state model

Transportation of water from roots to the leaves is a transient process which is influenced by fluctuation of evaporative demand in atmosphere and change in stomatal resistance (**Sperry et al., 2008**). Due to transpirational flow water potential declines in the xylem vessels and water moves in the vessels both radially and laterally. During movement of water, storage elements of xylem conducting vessels (parenchyma cells) store and release water depending upon need. This hydraulic storing process is analogous to electrical capacitance which is defined by the ratio of water content in tissues to the change in water potential (**Hunt and Nobel, 1987; Schulte et al., 1987**).

Study of hydraulic architecture has been a key topic amongst researchers since the pioneer effort by **Zimmermann (1978)**. For model simplifications a plant is considered as unbranched catena with series of resistance elements for root, stem and leaf. Due to the simplifications there are chances of errors in the model of water flow where branching is ignored (**Richter, 1973**). Again, some researchers argue that a plant with unbranched catena can also predict potential values at leaf cross-section for a steady state model. But an unbranched model might not correctly represent the water flow dynamics model within the

tree crown (**Edwards et al., 1986**). A full dynamic model for a branched catena was developed by **Tyree (1988)** to determine the changes of plant water potentials.

The primary tissue responsible for movement of water, nutrients and phytohormones from roots to leaves is xylem. Vessel members and tracheids are the two types of xylem vessel elements. Tracheids are generally lengthy than the vessel elements with tapered ends and large no. of pits. Pits produce enough resistance to the movement of water flow. Vessel members are of shorter length with constant diameter and connected in series. Perforation plates which divide the vessel members exert low flow resistance (**Myburg and Sederoff, 2001**).

During motion of water molecules from the stem xylems to leaf, the water column experiences substantial amount of resistance from the stomatal aperture. Since four decades, regulation of stomatal valves has been commonly discussed by Jarvis-Stewart model (**Jarvis, 1976; Stewart, 1988**) where stomatal resistance is a function of different environmental factors multiplied in series. **Cowan (1972)** developed a hydromechanical model analogous to electrical system based on water transfer functions that describes various aspects of stomatal behavior. **Dickinson (1984)** provided a simple representation of the effect of ambient temperature on stomatal resistance. He also parameterized the effect of photo synthetically active solar radiation on stomatal behavior. A relationship between vapor pressure deficit and stomatal resistance was adopted by **Jarvis (1976)** to show a linear increase of resistance with atmospheric vapor pressure deficit. Leaf water potential also influences diurnal change of stomatal resistance which can be expressed as hyperbolic function (**Ridder and Schayes, 1997**).

Effect of different microclimatic conditions (e.g. air temperature, light, relative humidity *etc.*) on stomatal conductance and leaf temperature was extensively described by **Janka et al. (2016)** using a mechanistic coupled model but yet to be validated under dynamic climatic conditions. Again prediction of water potential at stem using time regression analysis was proposed by **Abrisqueta et al. (2015)** assuming linear relationships between soil-plant-atmosphere variables. However, later on they (**Valdés-Vela et al., 2015**) showed a soft computing method to predict stem water potentials by approximating non-linear systems.

Transpiration is a necessary consequence results from photosynthesis. It is a molecular diffusion process through the intercellular spaces of leaf. An electrical analogy of transpiration process was introduced by **Chamberlain and Chadwick (1953)** which

originates from the difference in water vapor pressure between sub-stomatal cavity and ambient air. Water vapor crosses a thin boundary layer adjacent to leaf surface which exerts significant resistance to the movement of water molecules on its path (**Gerosa et al., 2012**). These molecules then enter into the turbulent surface layer of air where they experience aerodynamic resistance (**Alves et al., 1998**). Aerodynamic resistance mainly governed by wind speed above the tree crown and by height of the plant.

All inhabitants in nature interact with their surroundings through exchange of energy. In other words, energy absorbed from the environment in terms of solar radiation is partitioned into various energy utilizing processes in a plant. These processes are photosynthesis, transpiration, storage for metabolism *etc.* A little portion is also reflected from the plant leaves and this is formulated by Stephan Boltzmann law. This model of leaf energy balance has been used to determine leaf temperature and transpiration for a wide range of environmental factors (**Shimizu et al., 2004; Lhomme et al., 1998**).

2.2 Bond Graph in Plant Physiology

Bond graph formalism is generally used in civil, electrical, mechanical and in mechatronics systems extensively, however, only a few projects have been taken to model plant physiological systems. Pioneer effort was made by **Allen (1978)** who developed a model of the CO₂ uptake by a leaf, the photosynthetic process and the translocation of photosynthetic material to other plant parts. Possibility of describing a plant with bond graphs was shown by **Smerage (1976)** without determining equations describing the system. **Miersch (1996)** made significant contribution in modeling and simulating plant behavior, but limited to very narrow sets of conditions. Calculations are mostly done for one specific plant and day by linearizing the model without taking environmental conditions into account.

2.3 Literature Gap

After extensive study of various research papers and books related to plant water dynamics and application of bond graph technique on plant physiology, it can be observed that there are many models exist that deals with plant water dynamics. Most of them are modeled considering as a steady state model and some of them as a transient model. Electrical analogy with RLC circuit theory has been implemented to model a few. Empirical relations have also been used to parameterize certain portions of a complete plant. But very few attempts have been made to implement bond graph tool on plant water flow dynamics.

2.4 Objective of Present Research

After studying various literatures on plant water dynamics and application of bond graph lexicon on plant physiology, various gap area have been found. It is also observed that study of plant behavior in response to environmental factors with the help of either empirical relations or fully experimental work is time consuming. Even certain functionalities of plant (e.g. flow rates at different plant organs) are extremely difficult to measure with experimentation. Therefore, application of bond graph technique to model plant communities facilitates an alternative regime to study plant behavior. The objectives of the present thesis work are

- To get a comprehensive picture of plant water transportation process in soil-plant atmosphere continuum
- To model a mechanical equivalent scheme from the physical principles behind the water uptake process
- To put the mechanical equivalence model into a structured graphical notation called bond graph
- To parameterize various standard elements required to build the bond graph model
- To study the effect of different environmental and physical factors on plant functionalities with the help of the model

Soil water potential is one of the important statuses of water in the soil-plant-atmosphere continuum. It is mainly the measure of water content present in soil. The amount of water content differs from soil to soil and depending upon the type of soils, plant functionalities vary. Various functionalities of a plant like flow rates, water potentials at different organs of the plant can be determined by observing the behavior of the hydraulic flow model in response to different soil water potential.

3.1 Hydraulic Flow Model of a Simple Plant

A widely used model in plant physiology that helps to describe the dynamics of water flow from root to leaf in a biological plant system is considered here. It uses Darcy's law to describe various resistances towards the flow through a plant either in cellular pathways or along the xylem vessels. The model also takes into account the capacitive effect of the plant organs. It comprises of different sets of variables essential for modeling.

3.1.1 Mechanical equivalence of a simple plant

While studying water dynamics of a plant the components involved in it need to be defined. A simplified model of a plant consists of a root, a stem and a big leaf is considered as shown in Fig. 3.1(a). The mechanical equivalence of the hydraulic architecture of the plant is modeled with mainly two sets of elements (spring and damper) along with a source of effort (Se) at the root compartment and a source of flow (Sf) at the leaf compartment as described in Fig. 3.1(b). The source of effort variable is the water potential of soil just adjacent to the root and the flow variable is volume flow rate of water vapor from the leaf.

3.1.2 Bond graph model of simple plant

The mechanical equivalence of a simple plant model is put into bond graph notation as described in Fig. 3.2. The root compartment includes soil water potential represented by Se -element and root xylem resistance (R_{rx}) which is represented by R -element (bond no. 2) connected to the 1_f -junction that represents volume flow rate of water at root xylem. The root xylem resistance (R_{rx}) which is the resistance that water encounters on its path from soil adjacent to the root through the root surface is in mechanically parallel with the soil water potential. This resistance depends upon soil water potential, nutrients, temperature, root age and health. But for modeling purpose, it is assumed as constant (effects of these factors are

not considered here). The soil water potential, Ψ_s is modeled with a source of effort element connected to 1_r -junction (bond no. 1).

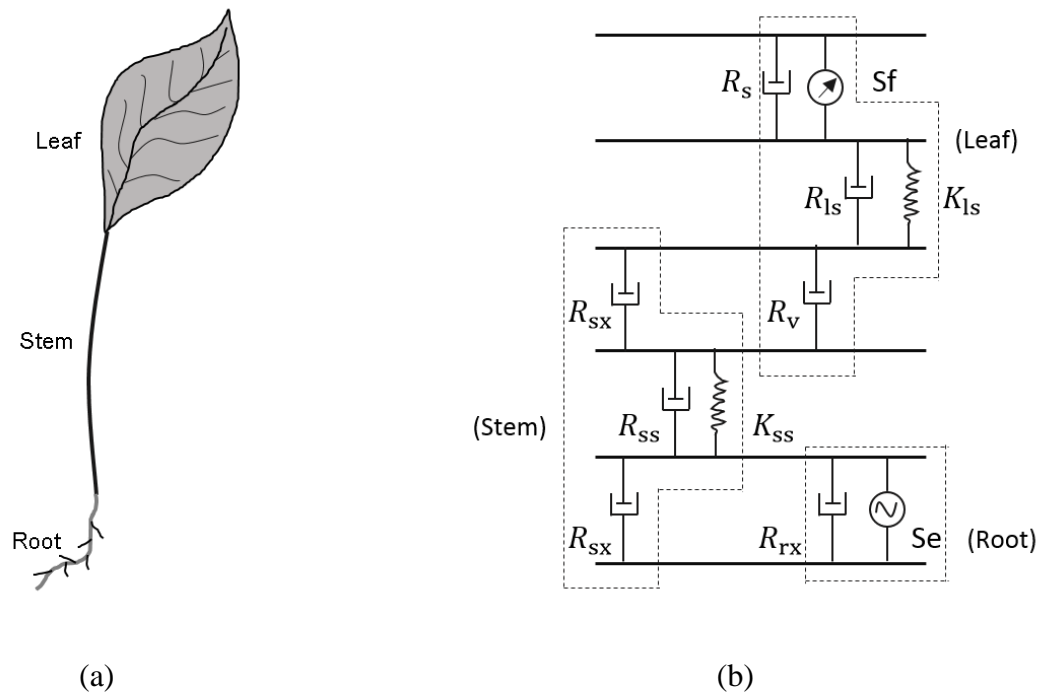


Fig. 3.1 (a) Hydraulic architecture of the simple plant and (b) mechanical equivalence

The shoot compartment is modeled with two stem xylem resistances (R_{sx}), a storage resistor, (R_{ss}) and a storage element with stiffness (K_{ss}). The last two elements are mechanically parallel to each other. Two xylem resistances and the mechanically parallel pair are connected in series in the mechanical equivalence scheme. These resistances which are represented by modulated R- elements are connected to two 1_s - junctions separately (bond nos. 6 and 12). This compartment of the model describes the radial flow into storage tissue adjacent to the xylem and lateral flow in the xylem.

The leaf compartment is similarly modeled with two resistive pathways that divides within the leaf; one path associated with the transpirational flow and the other with the flow in and out of the protoplasmic storage element. The leaf protoplast consists of a storage resistor, R_{1s} and a storage element with stiffness K_{1s} . These parallel pairs of resistances are connected in series with the leaf vein resistance R_v and stomatal resistance R_s . The leaf vein and the stomatal resistance are represented by two R- elements which are connected to two 1_l - junctions separately (bond nos. 14 and 20).

e_s (bond no. 29) are connected to the 1-junction to represent vapor pressure deficit ($e_s - e_a$) between the substomatal cavity and ambient air.

3.2 Influencing Parameters of Hydraulic Flow Model

Soil water potential, stem xylem resistance, leaf resistance and transpiration are the most influencing parameters for hydraulic flow model. So, effects of these parameters are considered in this model.

3.2.1 Soil water potential (Ψ_S)

Soil water potential in an initially wet soil has been considered as a source of effort (bond no. 1) which dries rapidly over a 5 days period in case of sandy soil (Slatyer, 1967). As soil moisture decreases, Ψ_S becomes more negative day by day as shown in Fig. 3.3. A well hydrated soil with constant (-0.15 MPa) soil water potential is also considered for comparing with the dry soil for various functionalities of the plant.

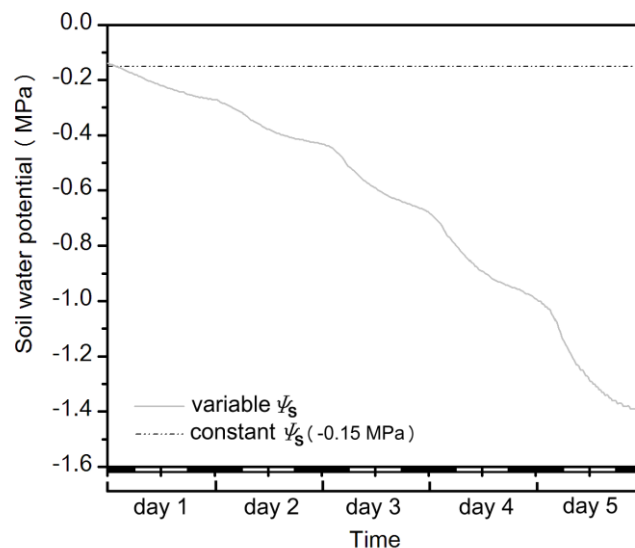


Fig. 3.3 Variation of soil water potential during 5 days

3.2.2 Stem xylem resistance (R_{sx})

The stem xylem resistance depends upon the rate of change in diameter of stem in a day. Fluctuations in diameter of stem is resulted from diurnal change in hydrostatic pressure inside the xylem vessels. Water molecules inside xylem vessels experiences large tension and then transmit it to the adjacent molecules when transpiration rate increases. Thus, the water molecules communicates tension effect to all adjacent molecules in the entire xylem vessels across the stem by decreasing hydrostatic pressure. This decrease in pressure can cause a tree

trunk to shrink during the daytime. During night time, tree trunk diameter expands due to increase in hydrostatic pressure in xylem. The diurnal change in stem diameter of a small plant is considered for modeling purpose as shown in Fig. 3.4(a) (Fujita et al., 2003). The stem xylem resistance changes with the change in stem diameter. The change in stem diameter is shown for a single day assuming same pattern of change in stem diameter for the remaining days. The dark period and day time are shown by black shades and white shades, respectively. The change in stem xylem resistance over a period of 5 days is shown in Fig. 3.4(b).

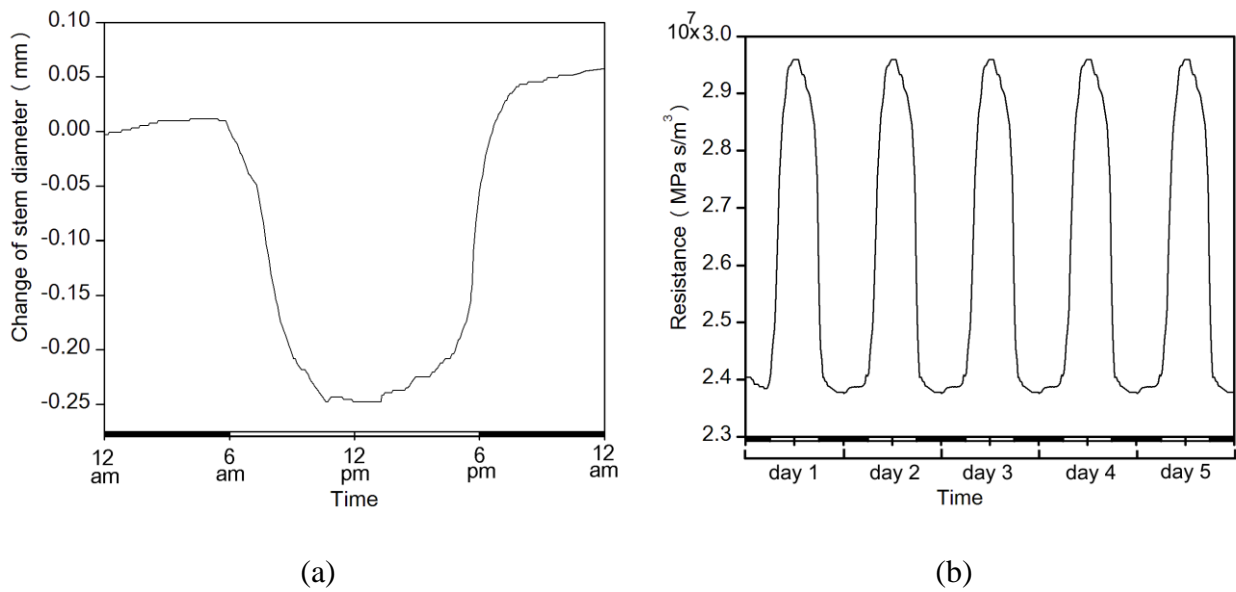


Fig. 3.4 (a) Diurnal change in stem diameter for a single day and (b) change in stem xylem resistance for a period of 5 days

For a stem xylem of length Δx_s with cross-sectional area of A_s the stem xylem resistance (R_{sx}) is calculated with the help of Ohm's electrical resistance analogy as

$$R_{sx} = \frac{\rho_s \Delta x_s}{A_s}, \quad (3.1)$$

where ρ_s is the hydraulic resistivity of the stem xylem. For several plants with xylem vessels, ρ_s varies between 100 – 500 MPa s m⁻². This stem xylem resistance is represented by elements MR6 and MR12 as shown in Fig. 3.2.

3.2.3 Leaf resistance

Leaf resistance largely depends upon the architecture of a leaf. It mainly comprises of stomatal resistance, cuticular resistance, leaf vein resistance and protoplasmic resistance. Water transportation takes place from stem xylem to leaf via petiole xylem and then enters into the leaf veins pathway and finally, it embedded into the leaf mesophyll and stomata. Cuticle is nearly impermeable to water as it is a waxy coating covering the leaf surface. Hence, major portion of the water vapor evaporates through the stomatal pores. Here, except stomatal resistance, all other resistances in the leaf compartment are considered as constant parameters. Therefore, measurement and study of environmental factors on stomatal behavior is an important issue.

Stomata can be considered as a hydraulically as well as chemically driven valve which opens to allow CO₂ uptake and closes to control water loss. The change in the size of the stomatal aperture regulates the process of transpiration and it is controlled by difference in turgor pressure between the leaf epidermis and guard cells. In general, stomatal aperture opens in day light and closes during the dark period except few plants like CAM plants which behave oppositely. The movements of the valves depend on various environmental factors such as incoming solar radiation, vapor pressure deficit, ambient temperature and CO₂ concentration in sub-stomatal cavity. Hence, stomatal resistance which is represented by elements MR20 and MR26 in Fig. 3.2 can be stated as (**Jarvis, 1976**)

$$R_s = r_{s(\min)} \cdot F(S) \cdot F(V_d) \cdot F(T) \cdot F(\Psi_1), \quad (3.2)$$

where $r_{s(\min)}$ is the minimum stomatal resistance observed in optimal conditions that depends on leaf stomatal density of a specie. $F(S)$, $F(T)$, $F(V_d)$ and $F(\Psi_1)$ are the factors associated with incoming solar radiation, ambient temperature, vapor pressure deficit of water and leaf water potential, respectively. Here, the influence of CO₂ concentration is neglected as it remains nearly constant throughout a day.

The factor $F(S)$ is a function of photo synthetically active solar radiation (f) which plays an important role in stomatal behavior. Photo synthetically active solar radiation is considered to be 55% of the global solar radiation. $F(S)$ and f can be expressed as (**Dickinson, 1984**)

$$F(S) = \frac{1 + f}{f + r_{s(\min)}/r_{s(\max)}}, \quad (3.3)$$

$$f = 0.55 \frac{2R_G}{L_I \cdot R_{GL}}, \quad (3.4)$$

where $r_{s(\max)} = 5000 \text{ sm}^{-1}$ for crops, L_I is leaf area index, R_G is global solar radiation and R_{GL} is the limit value of solar radiation with a value of 100 Wm^{-2} .

The effect of vapor pressure deficit of the atmosphere can be expressed as (**Jarvis, 1976**)

$$F(V_d) = [1 - \beta(e_s(T_a) - e_a)]^{-1}, \quad (3.5)$$

where β is the species specific parameter with a value of 0.025 hPa^{-1} for coniferous forest (HAPEX-MOBILHY dataset). The term $[e_s(T_a) - e_a]$ represents atmospheric vapor pressure deficit, where e_a is water vapor pressure of ambient air and e_s is water vapor pressure (Pa) of air in saturated condition.

The vapor pressure of air in saturated condition can be evaluated with the help of Tetten-Murray equation as

$$e_s(T_a) = 611 \exp[17.269(T_a - 273)/(T_a - 36)]. \quad (3.6)$$

Again, the vapor pressure of ambient air can be calculated by the following relation

$$e_a = R_H \cdot e_s(T), \quad (3.7)$$

where R_H is the relative humidity of ambient air.

The factor $F(T)$ introduces the effect of air temperature on the stomatal resistance as expressed in the following relation (**Dickinson, 1984**)

$$F(T) = [1 - 0.0016(298 - T_a)^2]^{-1}. \quad (3.8)$$

The dependence of water stress on stomatal resistance can be expressed by the following hyperbolic function (**Ridder and Schayes, 1997**)

$$F(\Psi_1) = (1 - \Psi_1/\Psi_c)^{-1}, \quad (3.9)$$

where Ψ_1 is bulk leaf water potential measured by introducing an effort detector in bond no. 16 and Ψ_c represents value of leaf water potential at which stomata closes completely and its value is assumed to be, $\Psi_c = -15$ MPa. Incoming global solar radiation (R_G), ambient air temperature T_a and relative humidity (R_H) of ambient air are measured with the help of Pyranometer (Kipp and Zonen, Netherlands) for 5 days (May 3rd to May 7th, 2015 measured at 30.36° N and 76.37° E) as shown in Fig. 3.5. The dark period and day time are shown by black shades and white shades, respectively.

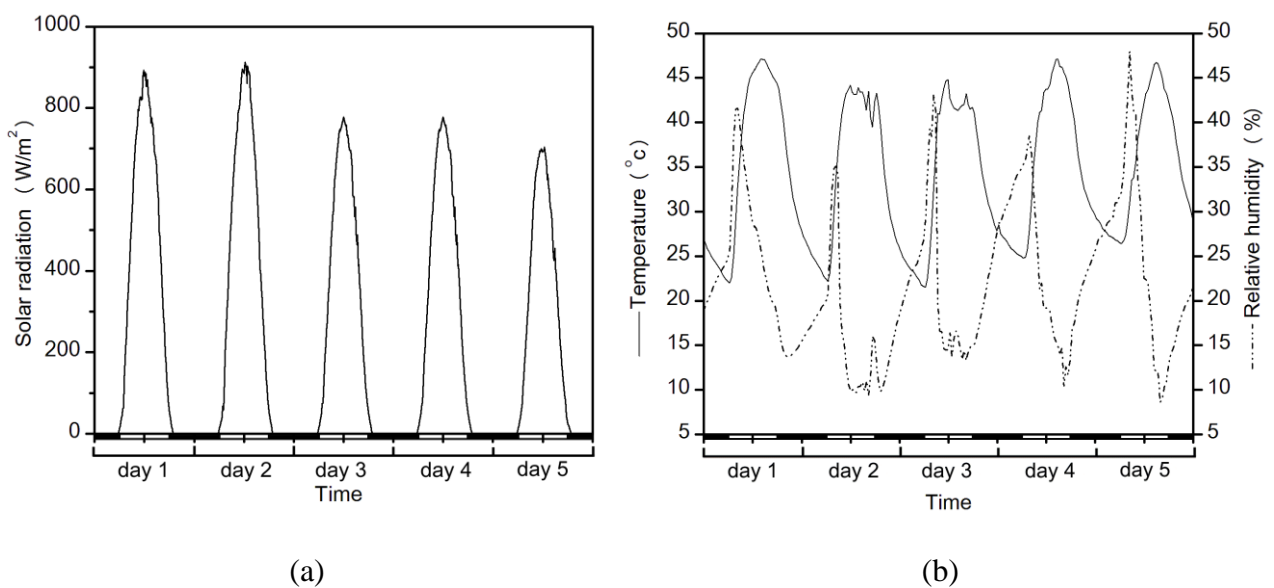


Fig. 3.5 (a) Incoming solar radiation and (b) ambient temperature and relative humidity of air for 5 days

3.3 Modeling of Transpiration

Transpiration is a molecular diffusion process where evaporation of water molecules takes place from the aerial parts of the plant to atmosphere. Transpiration process can be modeled through the Ohm's analogy formulated by **Chamberlain and Chadwick (1953)**. Transpirational flow i.e. volume flow rate (\dot{V}_t) of water is analogous to electric current flowing through a conductor from a point of higher potential to a lower one and this current originates from the electric potential difference.

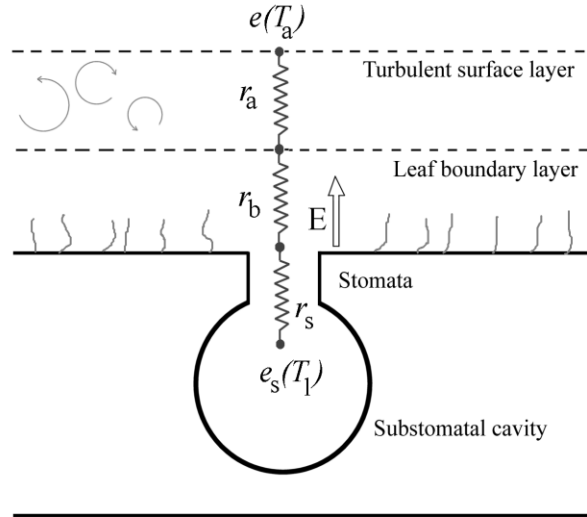


Fig. 3.6 Schema of transpiration process from stomata to atmosphere

The driving potential of transpiration is the vapor pressure difference between sub-stomatal cavity $e_s(T_l)$ at saturated condition and ambient air $e(T_a)$. During exchange of water vapor, the transpiration stream experiences resistances offered by the stomatal opening (R_s), laminar boundary layer (R_b) and turbulence boundary layer (R_a) where wind-speed plays an important role (Fig. 3.6). These resistances are considered to be in series connection as water vapor has to cross these layers one after another before it is lost in the atmosphere (Vermeulen et al., 2012). The transpirational flow rate, \dot{V}_t (m^3/s) can be expressed with the help of following relation

$$\dot{V}_t = \frac{e_s(T_l) - e(T_a)}{R_s + R_b + R_a}, \quad (3.10)$$

where T_a and T_l are temperature ($^{\circ}\text{K}$) of air and leaf respectively, e is vapor pressure of water in ambient air and e_s is vapor pressure of water in saturated air at leaf temperature. This transpirational flow rate is measured by introducing a flow detector to the 1-junction and then represented in modulated source of flow element MSf21 (Fig. 3.2).

Water vapor after experiencing stomatal resistance enters into the first layer of air at the vicinity of the leaf, i.e. boundary layer where air is motionless. This layer produces significant amount of resistance to the transpiration stream. Boundary layer resistance R_b (sm^{-1}) depends upon the boundary layer thickness and molecular properties of the diffusive substance which can be expressed as (Gerosa et al., 2012)

$$R_b = (Z_2 - Z_1)/D_{H_2O}, \quad (3.11)$$

where D_{H_2O} is diffusivity of water vapor in air and $(Z_2 - Z_1)$ is boundary layer thickness of the leaf. Equation (3.11) is used to define boundary layer resistance which is represented by the element R24 as shown in Fig. 3.2.

Aerodynamic resistance R_a (sm^{-1}) depends upon properties of turbulent surface layer and its value is greatly affected by the wind speed and plant height. It is represented by the resistive element R22 and can be formulated as (Alves et al., 1998)

$$R_a = \frac{\ln[(z - 0.67h_p)/0.123h_p] \cdot \ln[(z - 0.67h_p)/0.012h_p]}{k^2} \cdot \frac{1}{u}, \quad (3.12)$$

where z is the reference level at which horizontal wind speed u (ms^{-1}) is measured, h_p is height of the plant, k is Von Karman's constant (0.35–0.42).

The term $e_s(T_1) - e(T_a)$ in Eq. (3.10) represents vapor pressure difference (V_D) between stomatal cavity and ambient air and this can be evaluated as

$$e_s(T_1) - e(T_a) = e_s(T_a) + S_d \Delta T - e(T_a), \quad (3.13)$$

where S_d (Pa/K) is the slope of saturated vapor pressure versus temperature curve evaluated at T_a ($^{\circ}\text{K}$) which is given by

$$S_d = \frac{4098 [611 \exp(17.27(T_a - 273)/(T_a - 36))]}{(T_a - 36)^2}. \quad (3.14)$$

Again, temperature difference between leaf and ambient air, ΔT can be estimated with the help of leaf energy balance which can be expressed as (Lhomme et al., 1998)

$$\Delta T = \frac{R_G - [A/(R_a + R_b + R_s)][e_s(T_a) - e_a]}{\rho C_p/R_b + AS_d/(R_a + R_b + R_s)}, \quad (3.15)$$

where R_G (Wm^{-2}) is incoming solar radiation absorbed by the leaf, $A = 0.622 \lambda \rho / P_{\text{atm}}$ is a dimensionless term with latent heat of evaporation $\lambda = 2257$ kJ/kg, ρ is the density of air (1 kg/m^3) and P_{atm} is atmospheric pressure (101 KPa). Since, storage, photosynthesis and energy radiated by the leaf are very less as compared to convection and transpiration, in the leaf energy balance ΔT is evaluated by neglecting these terms.

The other parameters required for simulation are summarized in Table 3.1 (Miersch, 1996; Slatyer, 1967; Alves et al., 1998).

Table 3.1 Values of various parameters

Components	Unit	Value
Root xylem resistance (R_{rx})	MPa s m ⁻³	4.44×10^{13}
Stem storage resistance (R_{ss})	MPa s m ⁻³	8.9×10^{12}
Stem storage capacitance (K_{ss})	MPa m ⁻³	0.55×10^{11}
Hydraulic resistivity of stem xylem (ρ_s)	MPa s m ⁻²	400
Air density (ρ)	kg m ⁻³	1
Boundary layer resistance (R_b)	MPa s m ⁻³	1.42×10^{11}
Leaf storage resistance (R_{ls})	MPa s m ⁻³	1.29×10^{11}
Leaf storage capacitance (K_{ls})	MPa m ⁻³	2.0×10^{10}
Leaf vein resistance (R_v)	MPa s m ⁻³	2.0×10^{13}
Minimum stomatal resistance ($r_{s(\min)}$)	MPa s m ⁻³	400
Diffusion coefficient of water vapor (D_{H_2O})	–	24×10^{-6}
Wind speed (u)	m s ⁻¹	0.88
Specific heat of air at constant pressure (C_p)	KJ kg ⁻¹ K ⁻¹	1.005
Critical soil water potential for stomatal closure (Ψ_c)	MPa	-15
Atmospheric pressure (P_{atm})	MPa	0.101325
Latent heat of evaporation for water (λ)	KJ kg ⁻¹	2257
Von Karman's constant (k)	–	0.4
Leaf area index (L_I)	m ² m ⁻²	2.32
Limiting value of solar radiation (R_{GL})	W m ⁻²	100

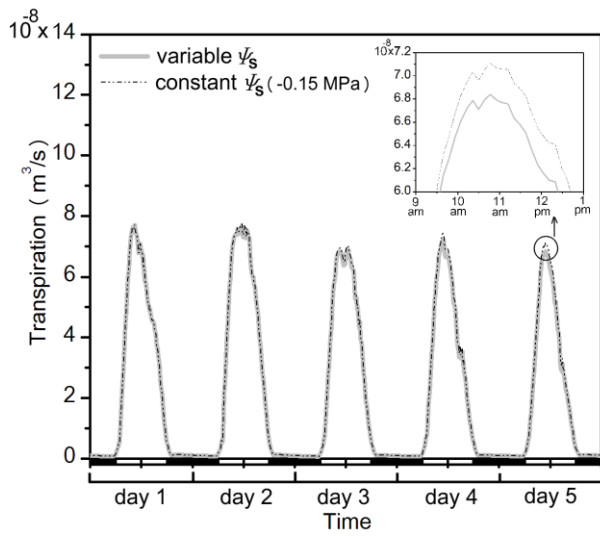
3.4 Simulation Results

Effect of soil water potential (Fig. 3.3) is taken into consideration to compare diurnal change of various functionalities of the plant for a period of 5 days. In case of variable Ψ_s , as amount of water in the soil decreases day by day, the plant experiences increase in water stress. This leads to the decrease in transpirational flow day by day and the difference at variable water potential (rapidly drying soil) and constant soil water potential (well hydrated soil) becomes maximum value (0.2×10^{-8} m³/s) on the 5th day (Fig. 3.7(a)) though, transpiration follows similar pattern in both the cases. During night time, flow rate is nearly zero and it starts

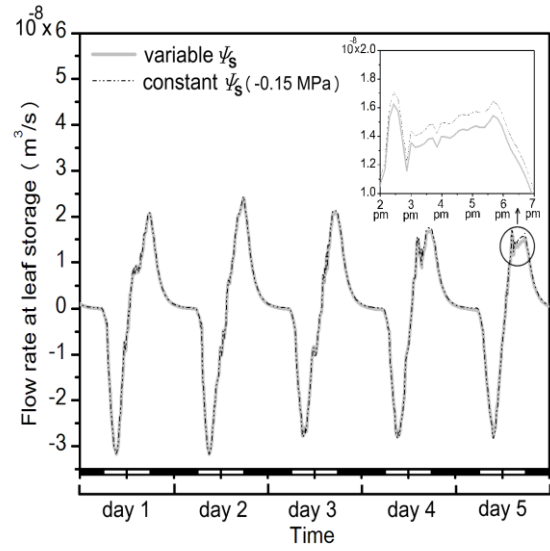
increasing after the start of day light. Maximum transpiration is observed during mid-day hours and again it starts decreasing.

Diurnal storage capacity and flow rates in leaf and stem storage elements varies with varying climatic conditions. Here, the effect of rapidly drying soil and well hydrated soil on flow rates at storage elements are described (Fig. 3.7(b) and Fig. 3.7(d)). Positive values of flow represent water movement into the storage element and negative values represent movement of water from the storage element. Water starts flowing into the storage element after the mid-day period in a day till the time of sun rise in the next day. Again, storage element releases water when transpiration rate is higher with a maximum value of 3.25×10^{-8} m³/s in day 1. The effect of variable Ψ_s on leaf storage flow rate is observed and flow rate into the storage element starts decreasing as Ψ_s decreases and it shows maximum effect on the 5th day with a difference in value of about 0.15×10^{-8} m³/s after mid-day period. Change in flow rate at stem storage also follows a similar pattern as described in Fig. 3.7(d). In Fig. 3.7(c), a maximum difference in flow rate is observed on the 5th day with a value of 0.25×10^{-8} m³/s during the mid-day period. During the dark period when transpiration ceases, a little amount of water transported through the stem xylem is taken by the storage elements.

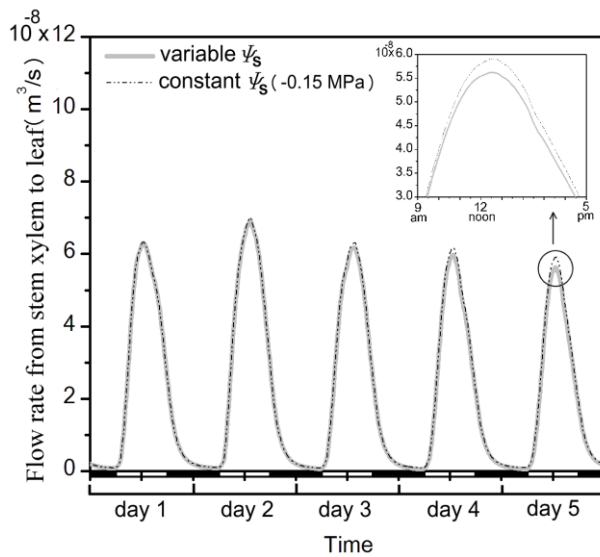
A significant effect of Ψ_s on water potential at various cross-sections of the plant is observed for a 5 days period. For well hydrated soil with constant Ψ_s , water potential at root, stem and leaf remains constant during the dark period every day, whereas a daily decrease in values is observed during the dark period in the case of variable Ψ_s (drying soil) as shown in Figs. 3.8(a)–(c). In both the cases, water potential at each cross-section becomes minimum value during the mid-day hours when transpiration rate is highest and starts increasing with the decrease in transpirational pull. During the dark period transpiration process ceases due to closing of stomatal pores and the water potentials at soil, root, stem and leaf become nearly equal. At dawn, when stomatal aperture opens water is released from the leaf due to transpiration and Ψ_{leaf} decreases. After a short lag, Ψ_{stem} and Ψ_{root} decrease. A maximum difference in the values of Ψ_{root} , Ψ_{stem} and Ψ_{leaf} at variable and constant Ψ_s is observed on the 5th day with a difference in value of nearly -1 MPa at each cross-section (Fig. 3.8(a)–(c)). The comparison between water potentials at different compartments of plant is shown in Fig. 3.8(d).



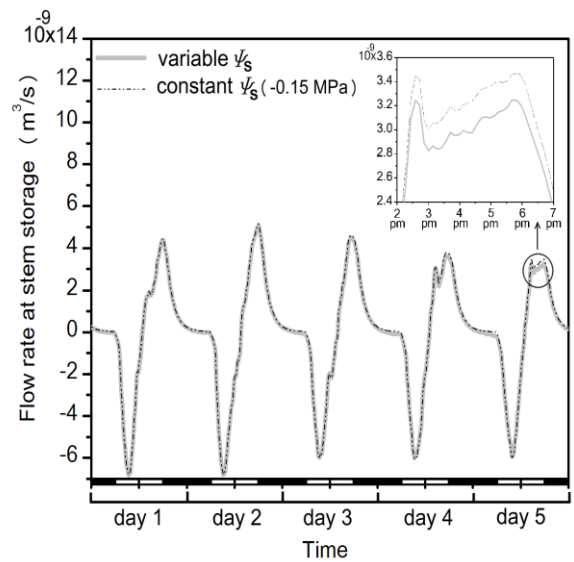
(a)



(b)



(c)



(d)

Fig. 3.7 Effect of constant and variable soil water potential on (a) transpirational flow rate, (b) flow rate into and out of leaf storage element, (c) flow rate from stem xylem to leaf and (d) flow rate into and out of stem storage element

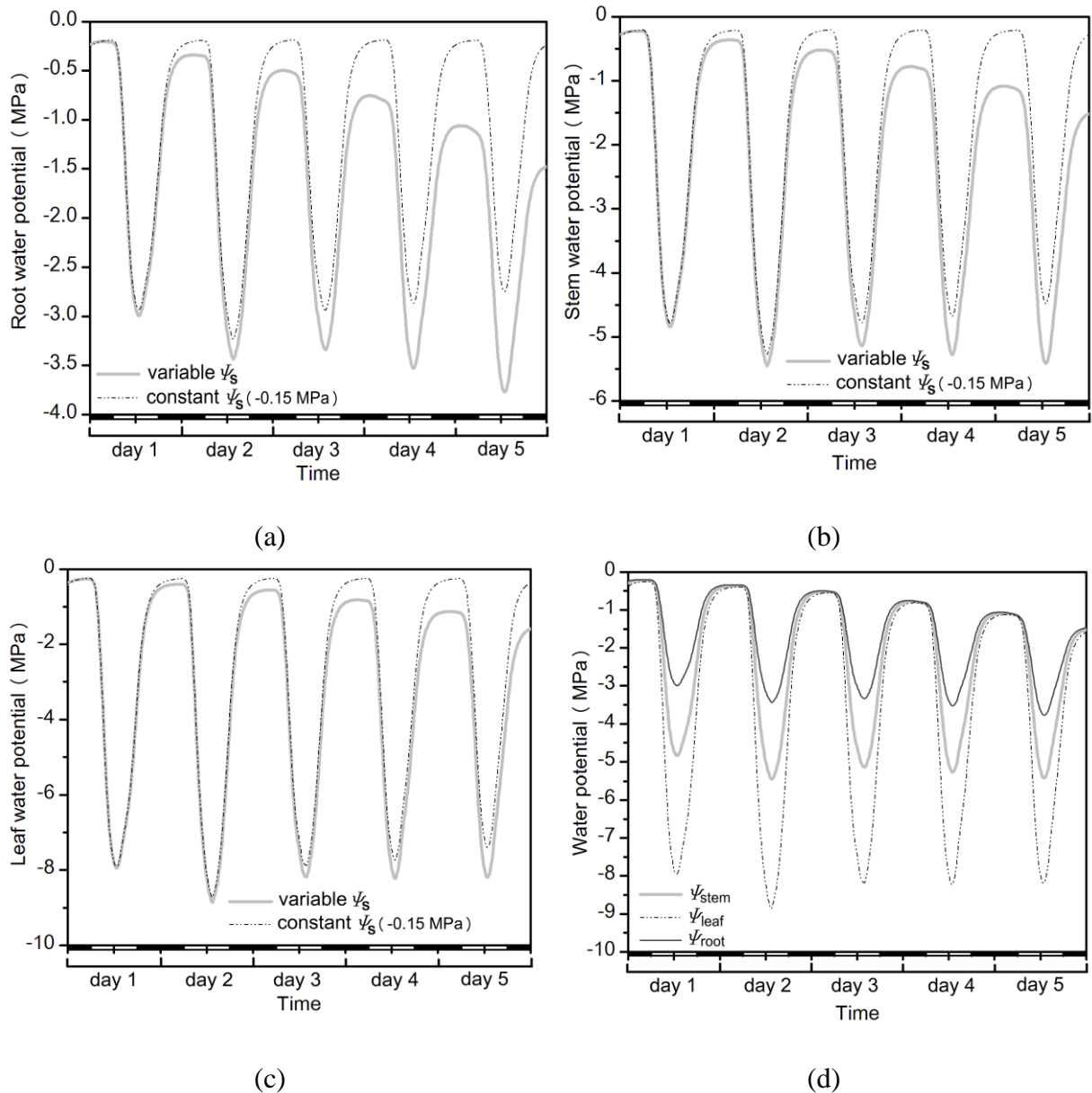


Fig. 3.8 Effect of constant and variable soil water potential on (a) water potential at root cross-section, (b) stem water potential, (c) leaf water potential and (d) water potential comparison at each compartment of plant

Stomatal regulation is a function of various environmental factors. Vapor pressure deficit, solar radiation and soil moisture content show varying effects on stomatal control and the influence of these factors are specie specific. Here, the cumulative effects of all the factors on stomatal resistance are observed for a period of 5 days (Fig. 3.9). During the dark period due to the absence of solar radiation, stomatal resistance (R_s) attains maximum value by closing stomatal aperture. In the morning period, stomatal aperture opens up quickly when solar radiation falls on plant leaf and R_s plummets to a minimum value of 0.3×10^6 MPa s m⁻³ just before the mid-day (day 1). However, in plant under stress, stomatal resistance is increased

by decreasing opening of stomatal aperture after mid-day period to reduce high loss of water through leaves. The response of stomatal resistance (R_s) to soil water potential is also depicted here. In the case of constant ψ_s , the maximum value of R_s observed during dark period is lesser than that of in the case variable, ψ_s . This difference in value becomes gradually significant with time and shows maximum difference on the 5th day.

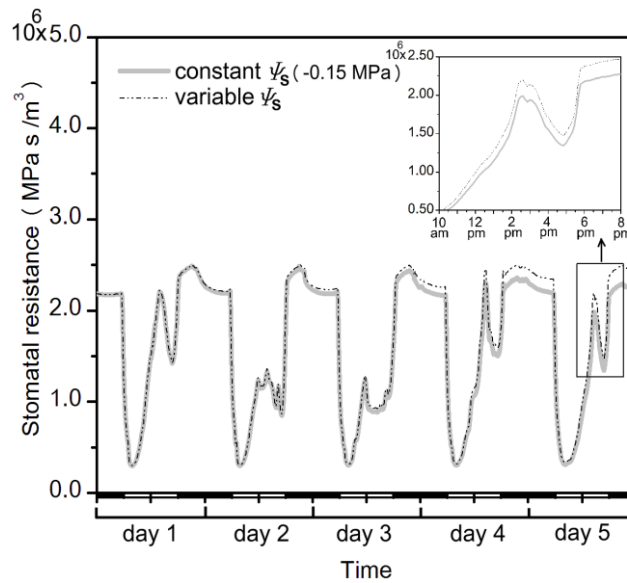


Fig. 3.9 Daily changes of stomatal resistance in response to constant and variable soil water potential

Solar radiation is electromagnetic wave emitted from the sun which provides energy for the metabolism of inhabitants on earth. Out of the three bands of solar radiation, the visible range or the photo-synthetically active radiation (PAR) is responsible for changing of stomatal conductance and hence, transpiration. The amount of transpiration changes depending upon the type of climate and weather. In a hot, sunny and less humid day transpirational flow will be greatest, where as in a cool, cloudy and humid day flow will be lowest. The relationship between transpiration and incoming solar radiation can be established with the help of leaf energy balance.

4.1 Leaf Energy Balance

Leaf energy balance follows conservation of energy principle where the incoming solar radiation (R_G) is partitioned into various energy utilizing processes. When incoming solar radiation falls on a leaf, a small amount of energy is re-radiated from the leaf, some part is lost in terms of sensible heat by convection process and some part is lost as latent heat resulting out of transpiration process. The remaining part is stored in the leaf for metabolic reaction purpose (Fig. 4.1). It can be represented as (Lhomme et al., 1998)

Incoming solar radiation = Re-radiation + Convection + Transpiration + Storage

$$R_G = \varepsilon_r + SH + LH + M \quad (4.1)$$

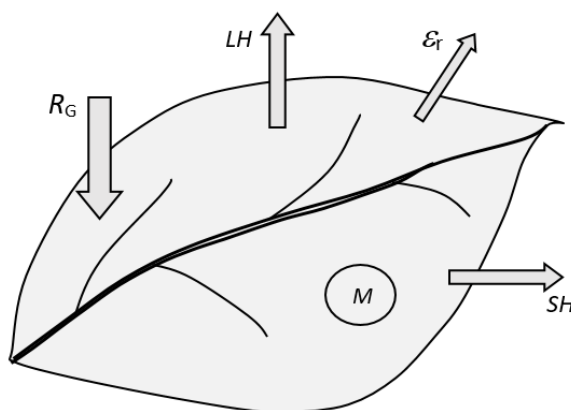


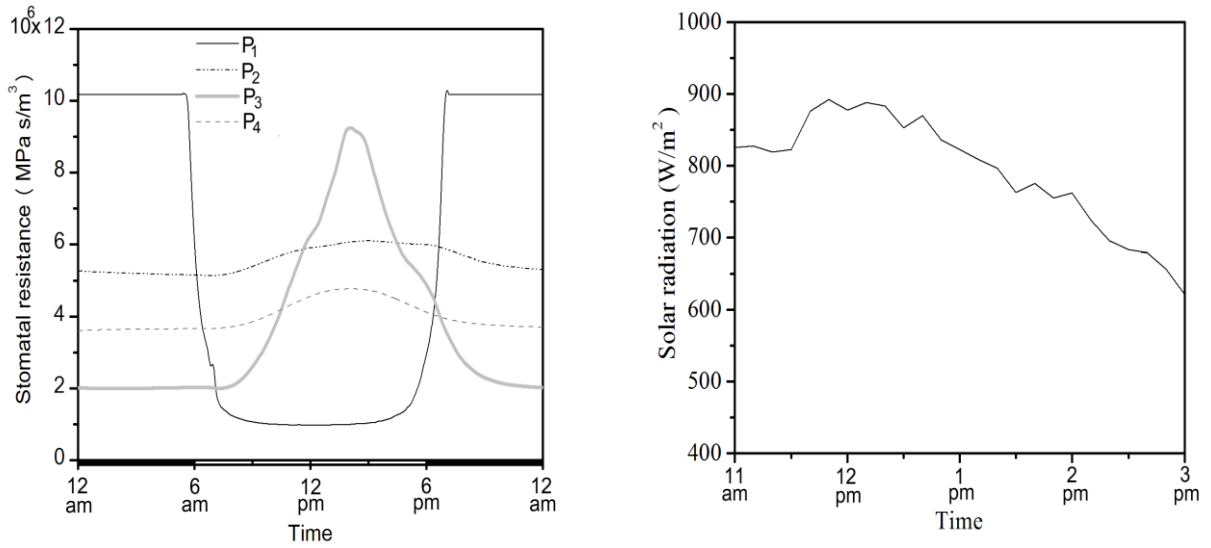
Fig. 4.1 Schema of leaf energy balance

In the hydraulic flow model only the energy utilizing processes, transpiration and convective heat loss is introduced. Re-radiation and storage is neglected for model simplification. Equation 4.1 is used to determine the temperature difference between ambient air and leaf which ultimately lead to the estimation of transpiration as described in Chapter 3 (Eq. 3.15). As transpiration is mainly controlled by opening and closing of stomatal aperture, therefore it is essential to study all the influencing factors on stomatal resistance. Out of all the influencing factors, a single factor which affects the stomatal behavior most is taken for further analysis of plant functionalities.

4.2 Influence of Various Environmental Factors on Stomatal Resistance

Stomatal resistance is a function of various environmental factors such as solar radiation, ambient temperature, vapor pressure deficit and leaf water potential as described in Chapter 3 (Eq. 3.2). The influence of every single factor on stomatal resistance can be observed from different plots, where the effect of one factor is taken into account keeping remaining factors constant as shown in Fig. 4.2(a). The plot P_1 is drawn with the help of Eq. 3.2 (Chapter 3) by taking only the variation of solar radiation factor, $F(S)$ (Eq. 3.3) while considering other factors as constant. Similarly, the plots P_2, P_3, P_4 are drawn by taking the variation of factors associated with vapor pressure deficit (Eq. 3.5), ambient temperature (Eq. 3.8) and leaf water potential (Eq. 3.9), respectively and keeping the remaining factors as constant in each plot. Though stomatal resistance model is a multiplicative model which shows a cumulative effect of all influencing factors, here the effect of every single factor is studied by observing their plots. It can be observed that all the plots except P_1 shows an increasing pattern of resistance during the day time whereas, P_1 shows an ideal behavior for stomatal resistance i.e., stomatal resistance decreases during day time which describes the effect of solar radiation on it.

Hence, solar radiation (R_G) is considered as the decisive influencing factor on stomatal resistance and its effects on water flow rates and plant water potential at various sections of the plant are further studied. Results are compared for two cases, one with variable R_G (Fig. 4.2(b)) and the other with constant R_G (425 Wm^{-2}) assuming constant solar radiation for a period of 4 hours between 11:00 am to 3:00 pm. Diurnal variation of R_G is measured on May 3rd, 2015 with the help of Pyranometer as described in Chapter 3.



P₁ – $F(S)$ variable; $F(V_d)$, $F(T)$ and $F(\Psi_1)$ constant
P₂ – $F(V_d)$ variable; $F(S)$, $F(T)$ and $F(\Psi_1)$ constant
P₃ – $F(T)$ variable; $F(S)$, $F(V_d)$ and $F(\Psi_1)$ constant
P₄ – $F(\psi_1)$ variable; $F(S)$, $F(V_d)$ and $F(T)$ constant

(a)

(b)

Fig. 4.2 (a) Effect of various factors on stomatal resistance and (b) solar radiation (day 1)

4.3 Simulation Results of Solar Radiation Effect

The hydraulic flow model as described in Chapter 3 (section 3.1) is simulated with the same parameters as mentioned in Table 3.1. Only the change in stomatal resistance is made by considering constant and variable solar radiation. Variable solar radiation effect on stomatal resistance is dictated by the plot P₁ and is implemented in the bond nos. 20 and 26 (Fig. 3.2).

4.3.1 Effect of solar radiation on volume flow rates

Rate of transpiration varies with varying R_G and it reaches a maximum value of about 8.5×10^{-8} m³/s during mid-day period while value of R_G is about 900 Wm⁻² (Fig. 4.3(a)). In case of constant R_G a steady increase in flow rate is observed at each cross-section of the plant over a span of 4 hours. For variable R_G , flow rate at leaf and stem storage shows similar pattern with maximum amount of flow rate out of the storage element at 11:00 am (Fig. 4.3(b) and 4.3(d)). This flow decreases with time and storage elements of leaf and stem start absorbing water after about 2:00 pm and then it increases. Again a significant increase in flow rate from stem xylem to leaf at variable R_G is observed from 11:00 am to 2:00 pm (Fig. 4.3(c)). After 2:00 pm this flow rate keeps on decreasing with the increase of water absorption rate into the storage elements.

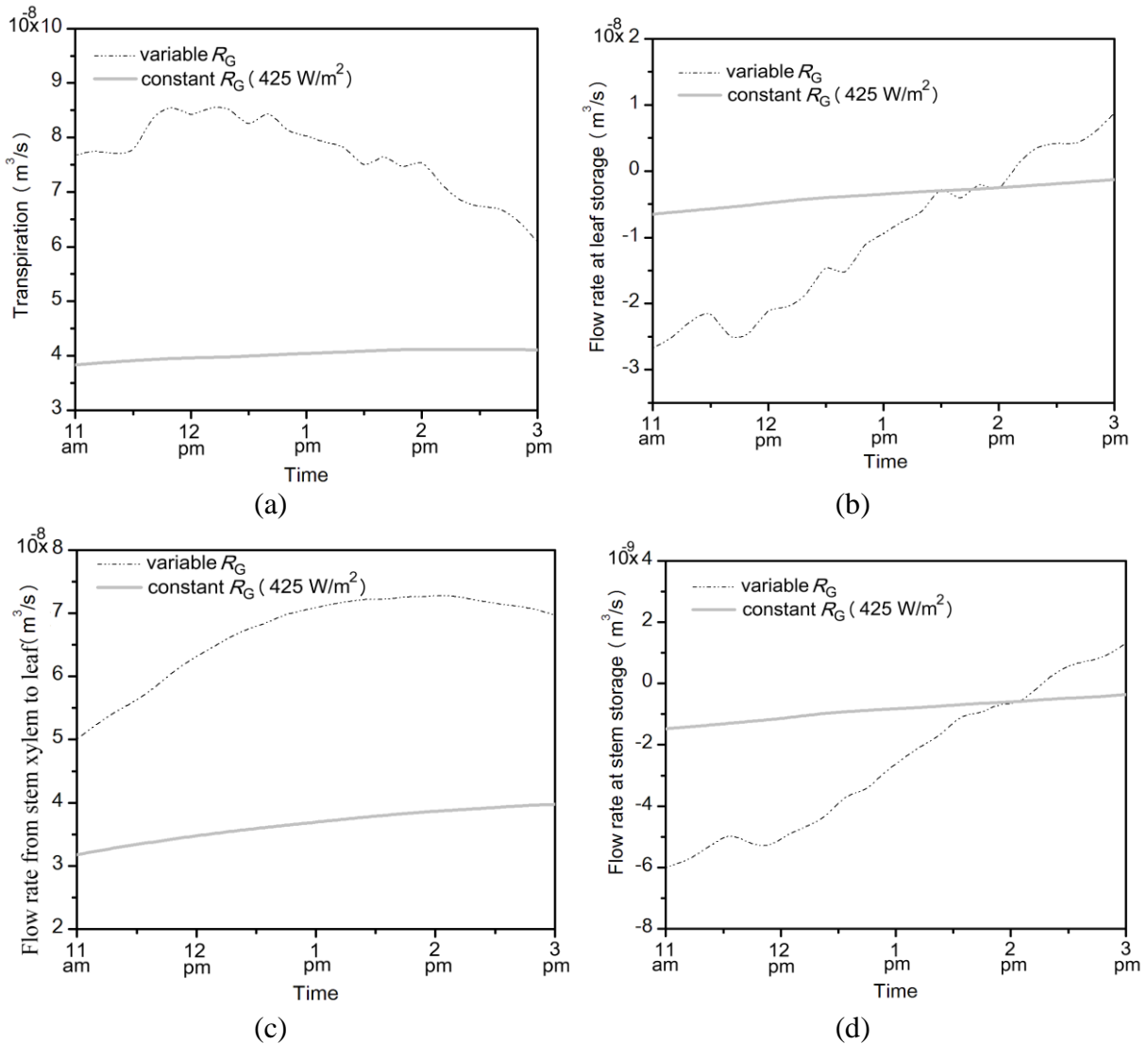


Fig. 4.3 Effects of constant and variable solar radiation on (a) transpiration, (b) flow rate into and out of leaf storage element, (c) flow rate from stem xylem to leaf and (d) flow rate into and out of stem storage element

4.3.2 Effect of solar radiation on water potentials

In case of variable R_G , water potentials at root, stem and leaf of plant become more negative with time till about 2:00 pm. Maximum drop is observed at leaf followed by stem and root with values nearly -9.5 MPa , -5.5 MPa and -3.5 MPa , respectively (Fig. 4.4(a) – (c)). In case of constant R_G a steady decrease in water potential at each cross section is observed and decrease in water potential in case of variable R_G is more as compared to constant R_G . Again at any instant of time water potential at leaf is minimum followed by stem and root water potential.

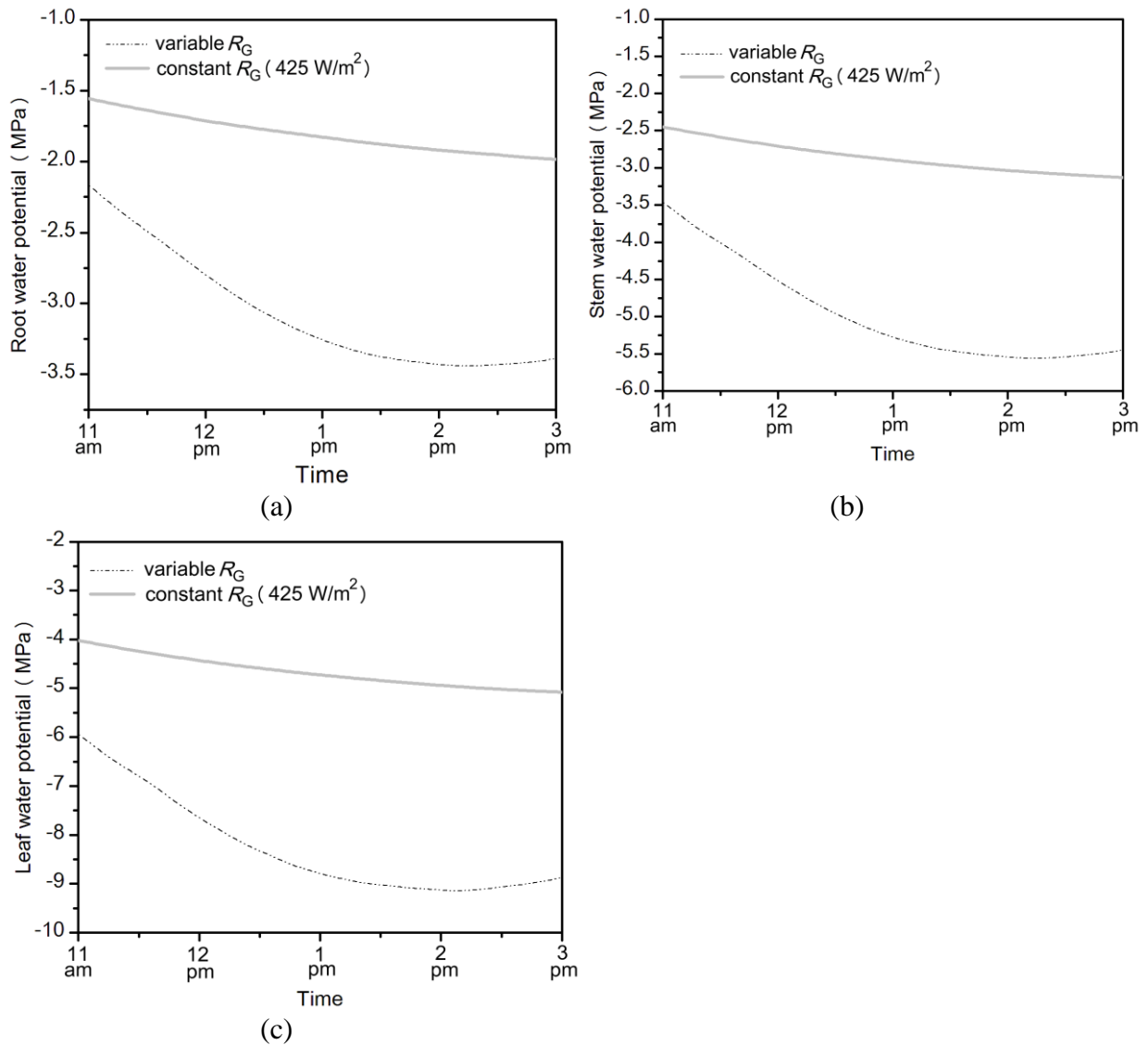


Fig. 4.4 Effects of constant and variable solar radiation on (a) water potential at root cross-section, (b) stem water potential and (c) leaf water potential

4.4 Effect of Plant Height on Various Factors

Plant height influences various factors like stomatal conductance, gravitational pull, leaf water potential, aerodynamic resistance etc. As plant height increases stomatal resistance also increases in order to control leaf water potential (Ψ_L). Also, with the increase in path length of water flow overall hydraulic resistance from soil to leaf increases to get rid of potentially damaging effects of plant like cavitation. Gravity always effects on water potential whether or not water flows through the xylem vessels. Probable variation of different resistive and capacitive elements with varying plant height is also neglected.

Over the last few decades most significant progresses are achieved in determining the effects of plant height on various factors. But the effect of plant height on aerodynamic resistance was a topic of less discussion. Therefore, without introducing all other factors only

the influence of plant height on aerodynamics resistance is taken into account to analyze different functionalities of plant.

Aerodynamic resistance (R_a) is the resistance to heat and water vapor transfer from leaf surface to ambient air above the canopy level.

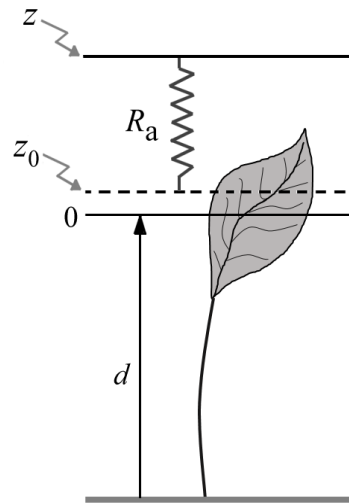


Fig. 4.5 Schematic representation of aerodynamic resistance on plant

Aerodynamic resistance can be formulated as (Alves et al., 1998)

$$R_a = \frac{\ln((z-d)/z_0) \cdot \ln((z-d)/z_{0h})}{k^2} \cdot \frac{1}{u}, \quad (4.2)$$

where z is the reference level above the canopy where wind velocity is measured, d is zero plane displacement ($0.67h_p$), z_0 is roughness length for momentum ($0.12h_p$) which is above the zero reference level where wind extinguishes, Z_{0h} is sensible heat roughness level ($0.1z_0$), k is Von Karman's constant, h_p is plant height measured from ground level and u is the wind velocity. After putting values in Eq. 4.2, it can be simplified to get the values of R_a for different plant heights.

4.5 Simulation Results of Plant Height Effect

The hydraulic flow model is simulated with the same parameters listed in Table 3.1. All other expressions for the bond graph standard elements are also implemented using the equations (Eq. 3.1 to Eq. 3.15) described in Chapter 3. Two kinds of plants, crop type and coniferous type with heights 1.5 m and 30 m respectively are considered to determine aerodynamic resistance and then implemented to estimate other plant functionalities.

4.5.1 Effect of plant height on volume flow rates

The differences in flow rates between the plants of different heights are significant during morning hours. In the case of 30 m height plant, nearly $0.2 \times 10^{-8} \text{ m}^3/\text{s}$ higher flow rate is observed than that of for the case of 1.5 m plant (Fig. 4.6(a)). Flow rate from stem xylem to leaf also shows a similar increase in value for the plant with greater height (Fig. 4.6(c)). Again, flow rates into the transpiration stream from stem and leaf storage elements show a slightly higher value for the plant with 30 m height during the period 7:00am to 10:00am (Fig. 4.6(b) and 4.6(d)).

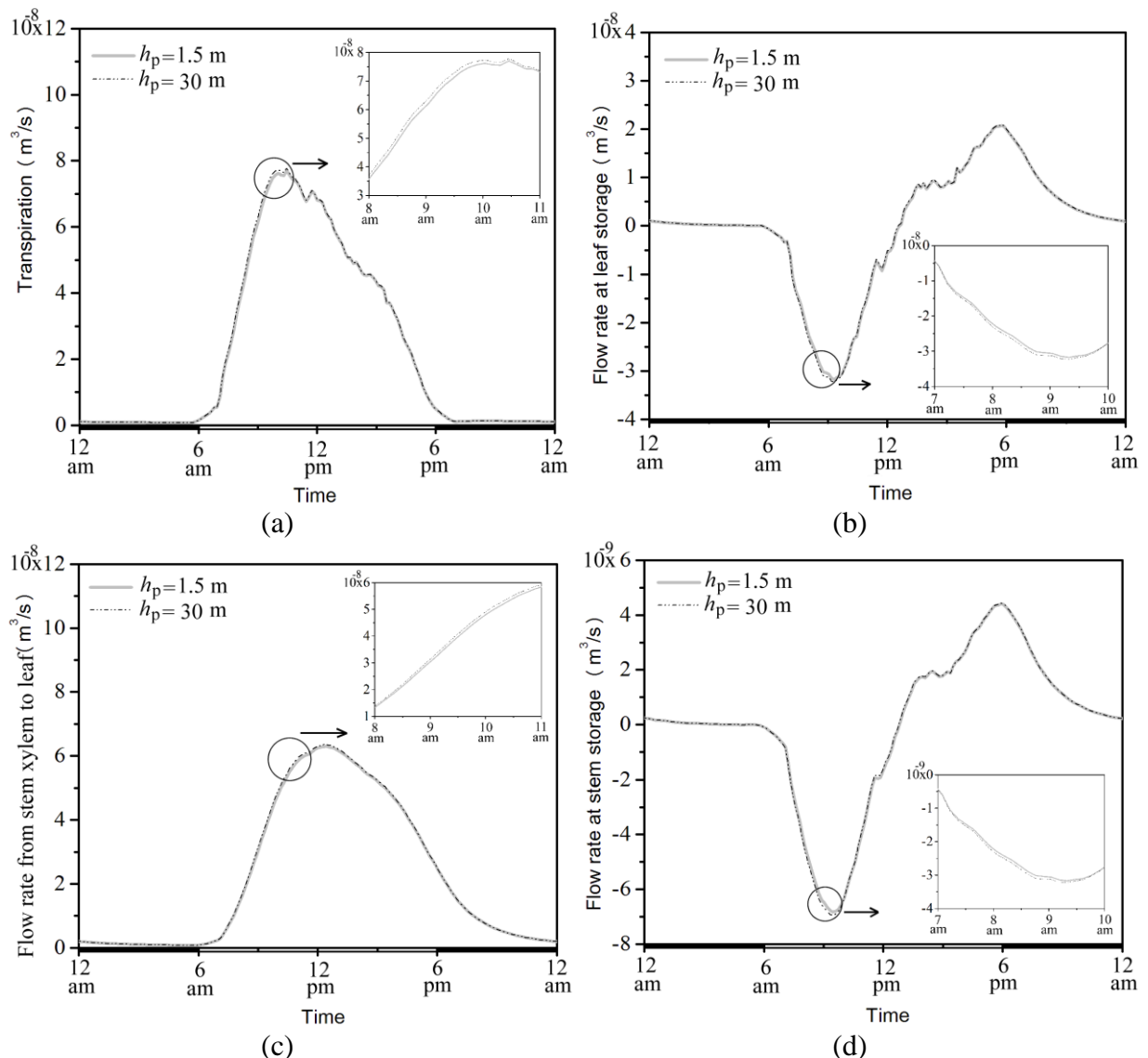


Fig. 4.6 Effect of plant height on (a) transpiration, (b) flow rate into and out of leaf storage element, (c) flow rate from stem xylem to leaf and (d) flow rate into and out of stem storage element

4.5.2 Effect of plant height on water potentials

Plant height also contributes to the variability of water potentials at various segments of a plant. With the increase in plant height, water potential at root, stem and leaf tend to decrease. The difference in potentials between the plants is observed to be nearly 0.06 MPa, 0.1 MPa and 0.2 MPa at root, stem and leaf respectively during the period from 10:00 am to 2:00 pm (Fig. 4.7(a), 4.7(b), 4.7 (c))

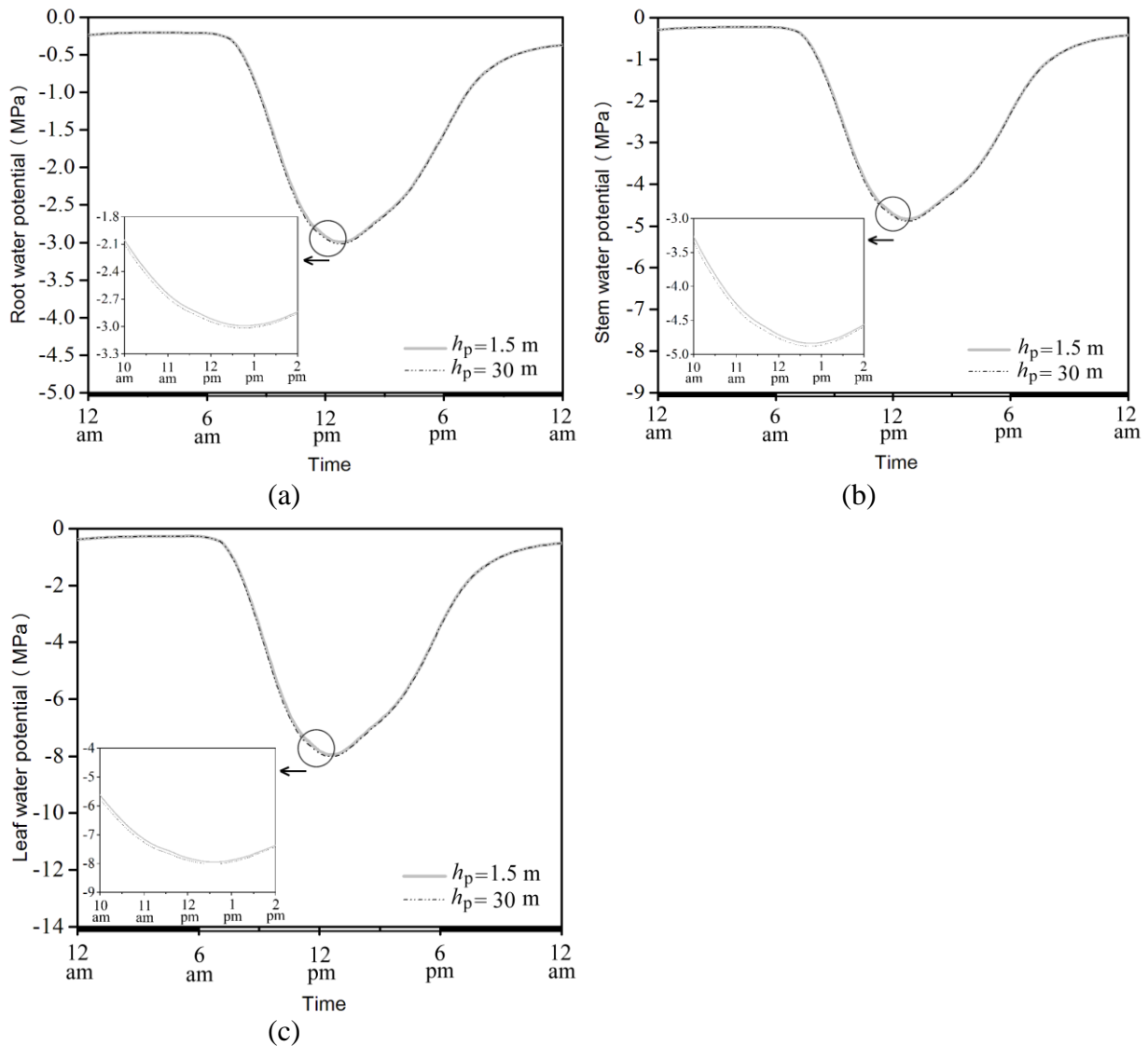


Fig. 4.7 Effect of plant height on (a) water potential at root cross-section, (b) stem water potential and (c) leaf water potential

5.1 Conclusions

Physical laws and empirical relations are used in the present research to determine interactions between the plant and environmental factors. Understanding the complete behavior of a plant in response to various factors is extremely troublesome by using only modeling techniques. However, implementation of bond graph on the hydraulic flow model of a simple plant is considered here to describe various functionalities of the plant and system behavior. Daily changes of various environmental factors such as soil water potential and solar radiation are taken into account to determine diurnal changes of water potential and flow rates at various sections of the plant. Dependence of plant height on flow rates and plant water potentials are also taken into consideration. In case of rapidly drying soil plant, transpiration and other flow rates at various cross-section of plant keep on decreasing with time due to less availability of water in the soil. Overall stomatal resistance also shows a similar decreasing behavior with time in the case of rapidly declining water potential due to the increase in water stress experienced by the stomatal aperture. Again, water potentials at leaf, stem and root become more negative in the case of rapidly decreasing soil water potential as compared to that of at constant soil water potential. Influence of solar radiation on the flow rates shows an increase in transpirational flow rates with increase in incoming solar radiation, whereas water potential at different parts of the plants shows reverse effect. Diurnal changes of flow rates and water potentials at root, stem and leaf in response to plant height shows a significant effect during morning. The plant with greater height transpires more as compared to the smaller height. This is due to the fact that as plant height increases, aerodynamic resistance decreases. On the other hand, water potentials at root, stem and leaf show more negative value for the plant with increasing height. Out of all the environmental and physical effects on plant functionalities it can be concluded that plant height effect is minimal as compared to soil water potential and incoming solar radiation.

The hydraulic flow model is developed considering some of the environmental and physiological conditions and tried to shape it as a realistic model. These conditions are subjected to mainly diurnal changes. However, seasonal changes can also play a vital role in the model development. Some of the environmental factors like precipitation, nutrient supply, wind speed, root age etc. greatly influence flow rates inside the plant. Flow rates also dependent on the plant species and health. But correct parameterization of all the influencing factors which describe biological behavior is extremely difficult and error prone. Assumption

of different resistance and capacitance elements lead to idealistic results up to certain extent. Up scaling of cellular level mechanisms to the overall plant responses is a cumbersome process and therefore, model simplification is extremely necessary.

5.2 Future Scope of Model Development

Though effort has been made to develop a merely realistic and general mechanistic model, there is still ample scope for further development of the model. Some ideas for future model development are suggested as follows:

- Instead of considering constant values for certain resistive and capacitive parameters, diurnal change of all those can be considered for better simulation results
- Influence of plant height on stomatal resistance and gravitational pull can be incorporated for better realistic results
- While formulating the leaf energy budget certain parameters like emissivity, storage and photosynthesis can be also be included
- There are possibilities of incorporating seasonal changes, nutrient supply, plant age and health in the model though it is extremely challenging

- Abrisqueta, I., Conejero, W., Valdés-Vela, M., Vera, J., Ortuño, M.F., Ruiz-Sánchez, M.C., 2015. Stem water potential estimation of drip-irrigated early-maturing peach trees under Mediterranean conditions. *Comp. Elect. Agric.* 114, 7–13.
- Allen, R.R., 1978. Bond graph models for plant bio systems. *Comp. Prog. Biomed.* 8, 149–164.
- Alves, I., Perrier, A., Pereira, L.S., 1998. Aerodynamic and surface resistances of complete cover crops: How good is the “Big Leaf”? *Transactions of the ASAE.* 41(2), 345–351.
- Cowan, I.R., 1965. Transport of water in the soil-plant-atmosphere system. *J Appl. Ecol.* 2(1), 221–239.
- Chamberlain, A.C., Chadwick, R.C., 1953. Deposition of airborne radioiodine vapor. *Nucleonics.* 11, 22–25.
- De Ridder, K., Schayes, G., 1997. The IAGL land surface model. *J Appl. Meteorol.* 36, 167–182.
- Dickinson, R.E., 1984. Modeling evapotranspiration for three-dimensional global climate models. *Climate Processes and Climate Sensitivity.* Amer. Geophys Union Geophys. Monogr. 29, 58–72.
- Dixon, H., Joly, J., 1895. On the ascent of sap. *Philos Trans Roy Soc B – Biol. Sci.* 186, 563–576.
- Edwards, W.R.N., Jarvis, P.G., Landsberg, J.J., Talbot, H., 1986. A dynamic model for studying flow of water in single trees. *Tree Physiol.* 1, 309–324.
- Fujita, K., Okada, M., Lei, K., Ito, J., Ohkura, K., Adu-Gyamfi, J.J., Mohapatra, P.K., 2003. Effect of P-deficiency on photoassimilate partitioning and rhythmic changes in fruit and stem diameter of tomato (*Lycopersicon esculentum*) during fruit growth. *J Exp. Botany.* 54, 2519–2528.
- Gerosa, G., Mereu, S., Finco, A., Marzuoli, R., 2012. Stomatal conductance modeling to estimate the evapotranspiration of natural and agricultural ecosystems. *Evapotranspiration– Remote Sensing and Modeling.* 18, 403–420.
- Hunt, E.R., Nobel, P.S., 1987. Non steady-state water flow for three desert perennials with difference capacitances. *Aus. J Plant Physiol.* 14, 363–375.
- Irvine, J., Grace, J., 1997. Continuous measurement of water tensions in the xylem of trees based on the elastic properties of wood. *Planta.* 202(4), 455–461.

- Janka, E., Körner, O., Rosenqvist, E., Ottosen, C., 2016. A coupled model of leaf photosynthesis, stomatal conductance and leaf energy balance for chrysanthemum (*Dendranthema grandiflora*). *Comp. Elect. Agric.* 123, 264–274.
- Jarvis, P.G., Edwards, W.R.N., Talbot, H., 1981. Models of plant and crop water use. *Math. and Plant Physiol.* 151–194.
- Jarvis, P.G., 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Philosophical Transactions of the Royal Society of London, Series B.* 273, 593–610.
- Lhomme, J.P., Elguero, E., Chehbouni, A., Boulet, G., 1998. Stomatal control of transpiration: Examination of Monteith's formulation of canopy resistance. *Water Resour. Res.* 34(9), 2301–2308.
- MacDougal, D.T., Shreve, F., 1924. Growth in trees and massive organs of plants: Dendrographic measurements. Carnegie Institute of Washington.
- Miersch, J., 1996. Bond graphs in modeling plant water dynamics. Thesis report, Electrical and Computer Engineering, University of Arizona, Tucson.
- Mukherjee, A. Karmakar, R., Samantaray, A.K., 2006. Bond graph in modeling, simulation and fault identification. FL: CRC Press.
- Myburg, A.A., Sederoff, R.R., 2001. Xylem structure and function. *Ency. Life Sci.* 2001.
- Richter, H., 1973. Frictional potential losses and total water potential in plants: a re-evaluation. *J Exp. Botany.* 24, 983–994.
- Shimizu, H., Runkle, E.S., Heins, R.D., 2004. A steady state model of prediction of poinsettia plant shoot-tip temperature. *J Amer. Soc. Hor. Sci.* 129(3), 303–312.
- Simonneau, T., Habib, R., Goutouly, J.P., Huguet, J.G., 1993. Diurnal change in stem diameter depend upon variation in water content: Direct evidence in peach trees. *J Exp. Botany.* 260, 615–621.
- Slatyer, R.O., 1967. Plant–water relationships. New York: Academic Press.
- Smerage, G.H., 1976. Matter and energy flow in biology and ecological systems, *J theor. Biol.* 57(1), 203–223.
- Smith, J.A.C, Schulte, P.J., Nobel, P.S., 1987. Water flow and water storage in Agave deserti: Osmotic implications of crassulacean acid metabolism. *Plant Cell Environ.* 10, 639-648.
- Sperry, J.S., Meinzer, F.C., McCulloh, K.A., 2008. Safety and efficiency conflicts in hydraulic architecture: scaling from tissues to trees. *Plant Cell Environ.* 31, 632–645.

- Stewart J.B., 1988. Modeling surface conductance of pine forest. *Agri. Forest Meteorol.* 43, 19–35.
- Tyree, M.T., 1988. A dynamic model for water flow in a single tree: evidence that models must account for hydraulic architecture. *Tree Physiol.* 4, 195–217.
- Valdés-Vela, M., Abrisqueta, I., Conejero, W., Vera, J., 2015. Soft computing applied to stem water potential estimation: A fuzzy rule based approach. *Comp. Elect. Agric.* 115, 150–160.
- Van den Honert, T.H., 1948. Water transport in plants as a catenary process. *Disc. Farad. Soc.* 3, 146–153.
- Vermeulen, K., Aerts, J., Dekock, J., Bleyaert, P., Berckmans, D., 2012. Automated leaf temperature monitoring of glasshouse tomato plants by using a leaf energy balance model. *Comp. Elect. Agric.* 87, 19–31.
- Zimmermann, M.H., 1978. Hydraulic architecture of some diffuse porous trees. *Can. J Botany.* 56, 2286–2295.

Mr. Bhriagu Kumar Lahkar completed his bachelor degree in Mechanical Engineering from Tezpur University (a Central University under Govt. of India), Tezpur, Assam in 2010. After completion his degree he joined at Larsen and Toubro Ltd., Vadodara, India where he was engaged with the department of Transportation and off Highway Vehicle. He served as a team leader for the project of *Design and development of engine peripheral component* (Euro-6, DAF Trucks, Netherlands). In 2014, he joined Master of Engineering program in CAD/CAM at Thapar University, Patiala with GATE score. During his ME program, he worked in the domain of *Plant water dynamics and application of bond graph in plant physiology* as a part of his master's thesis. Recently, he submitted a paper entitled 'Hydraulic flow model of plant organs in response to physical and environmental factors' in the journal 'Computer and Electronics in Agriculture'.

Publication in International Journal:

Lahkar B., and Bera T. K. "Hydraulic flow model of plant organs in response to physical and environmental factors", *Computer and Electronics in Agriculture, Elsevier*. (**Under Review**)