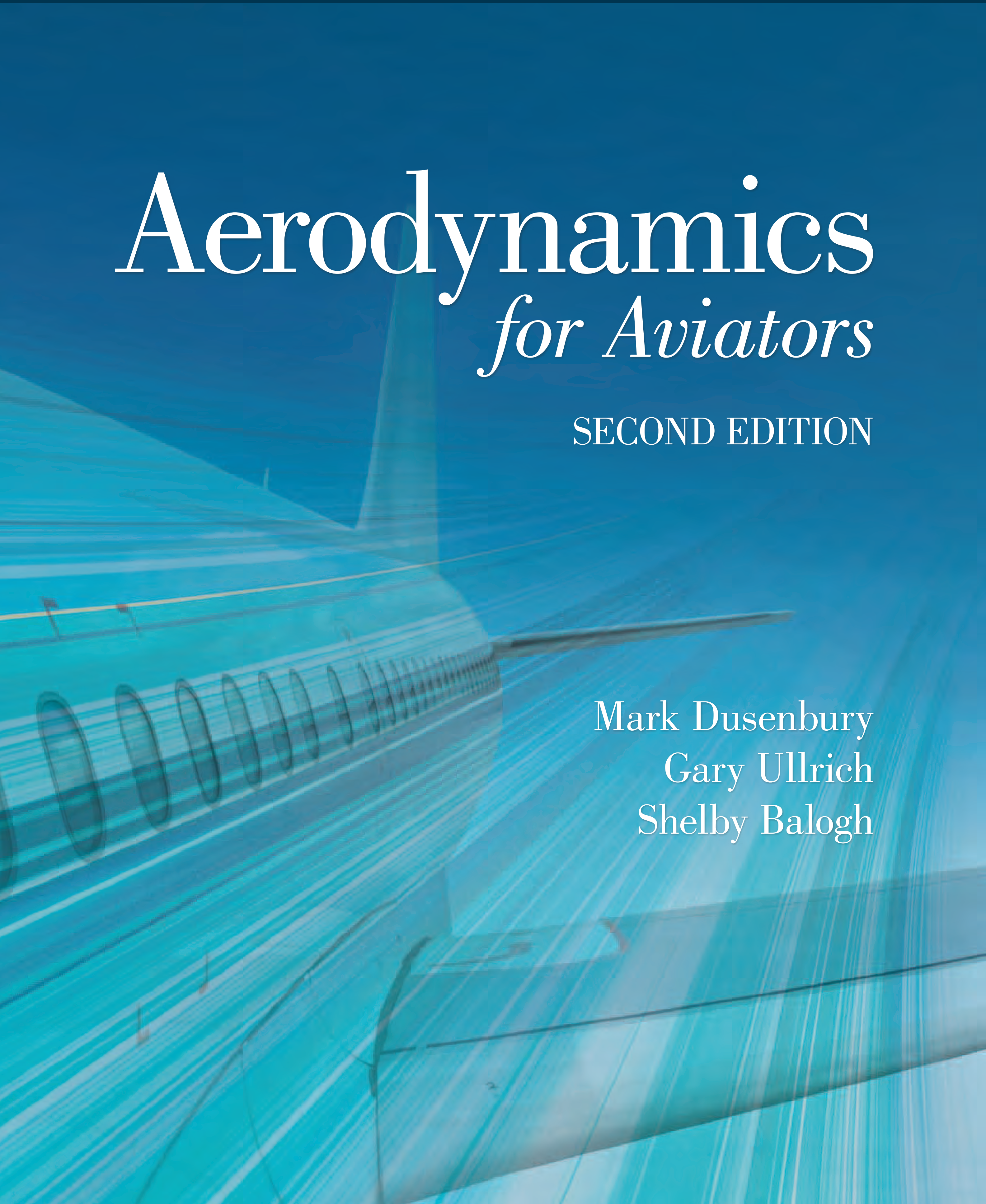
Aerodynamics
for Aviators

SECOND EDITION

Mark Dusenbury
Gary Ullrich
Shelby Balogh



Aerodynamics
for Aviators

Mark Dusenbury
Gary Ullrich
Shelby Balogh

SECOND EDITION

Aviation Supplies & Academics, Inc.
Newcastle, Washington

Aerodynamics for Aviators
Second Edition
by Mark Dusenbury, Gary Ullrich, and Shelby Balogh

Aviation Supplies & Academics, Inc.
7005 132nd Place SE
Newcastle, Washington 98059-3153
asa@asa2fly.com | www.asa2fly.com

Second edition published 2016 by Aviation Supplies & Academics, Inc.
First edition published 2012, Kendall Hunt. First edition eBook published 2013, University Aviation Press.

Many figures in this book are derived from material in the FAA's *Aerodynamics for Naval Aviators* (NAVWEPS 00-80T-80) and *Pilot's Handbook of Aeronautical Knowledge* (FAA-H-8083-25A).

Cover images—Aircraft: ©istock.com/Laurent davoust. Aerodynamic airflow: ©istock.com/nadla.

ASA-AERODYN-2
ISBN 978-1-61954-333-1

Printed in the United States of America

2020 2019 2018 2017 2016 9 8 7 6 5 4 3 2 1

Library of Congress Cataloging-in-Publication Data:

Names: Dusenbury, Mark, author. | Ullrich, Gary M., author. | Balogh, Shelby D., author.
Title: Aerodynamics for aviators / by Mark J. Dusenbury, Gary M. Ullrich, and Shelby D. Balogh.
Description: Second edition. | Newcastle, Washington : Aviation Supplies & Academics, Inc., [2016] | Includes index.
Identifiers: LCCN 2016009293 | ISBN 9781619543331 (hardcover) | ISBN 1619543338 (hardcover)
Subjects: LCSH: Aerodynamics—Textbooks. | Airplanes—Piloting—Textbooks. | Airplanes—Performance—Textbooks.
Classification: LCC TL570.D874 2016 | DDC 629.132/3—dc23
LC record available at http://lccn.loc.gov/2016009293

Contents

This book is dedicated to Al Baker.

Foreword

Aerodynamics for Aviators is not a book of new knowledge. It is, rather, an arrangement of existing knowledge from many sources into a concise presentation of what pilots need to know about aerodynamics. The three authors have emphasized the practical side of aerodynamics, giving the pilot a basic understanding of the physical laws that make an aircraft fly.

This is the second edition of their textbook, which adds material on high lift-devices and high-altitude aerodynamics. This textbook is a great addition to any pilot's library, whether you are a student, professional, or military pilot.

Glen "Manny" Mancuso
Captain, Southwest Airlines

About the Authors

Mark Dusenbury is an Associate Professor for the John D. Odegard School of Aerospace Sciences at the University of North Dakota in Grand Forks, North Dakota. Before coming to the University of North Dakota, Professor Dusenbury was an airline pilot for American Eagle Airlines, and a member of the United States Marine Corps Reserves. He also holds a commercial pilot certificate with instrument, single, and multi-engine ratings, and is a certified flight instructor for single, multi-engine, and instrument airplane.

Gary M. Ullrich is an Associate Professor for the John D. Odegard School of Aerospace Sciences at the University of North Dakota in Grand Forks, North Dakota. Before joining the University of North Dakota, Professor Ullrich was a Test Group Pilot for Flight Safety, Adjunct Assistant Professor for Embry Riddle Aeronautical University, and instructor/evaluator pilot with the United States Air Force. Professor Ullrich is a commercial pilot with multi-engine, instrument, and Boeing 720 and 707 type ratings.

Shelby Balogh is a data and analytics scientist at GE Aviation. Before coming to General Electric, Shelby was a lecturer at the John D. Odegard School of Aerospace Sciences and an airline pilot for Horizon Air. He holds an Airline Transport Pilot (ATP) certificate with instrument and multi-engine ratings, and is a Certified Flight Instructor for airplane single, multi-engine, and instrument airplane.

The Beechcraft Bonanza entered service in 1947, becoming one of the most popular general aviation airplanes of all time. Aerodynamically, the Bonanza has stood the test of time, and in addition, has a very distinguishing feature: the V-Tail. The last V-Tail Bonanza was produced in 1982; however, the tail design has made its way into the modern Cirrus Jet.

Introduction

What is aerodynamics? The word comes from two Greek words: *aerios*, concerning the air, and *dynamis,* which means force. Aerodynamics is the study of forces and the resulting motion of objects through the air. Judging from the story of Daedalus and Icarus, humans have been interested in aerodynamics and flying for thousands of years, although flying in a heavier-than-air machine has been possible only in the last hundred years.

In this age of manmade satellites spinning around the earth, and aircraft with capabilities of climbing to 350,000+ feet and of attaining velocities of nearly ten times the speed of sound, it becomes evident that science has made great progress since the time of the Wright brothers' first successful flights in powered heavier-than-air machines. Aerodynamics affects the motion of any object through air—a large airliner, an unmanned aerial vehicle, a glider, a model rocket, a beach ball thrown near the shore, or even a kite flying high overhead. Many people do not realize that the curveball thrown by big league baseball pitchers gets its curve from aerodynamics.

The pilot of today must have a greater technical knowledge and understanding than the pilot of even 15 years ago. Today's multimillion-dollar aircraft are highly complex machines with many more systems and aerodynamic problems than their predecessors. To operate today's aircraft, a pilot must have more than just a basic knowledge of principles of flight. The safety and effectiveness of flying operations will depend greatly on the understanding and appreciation of how and why an airplane flies. For this reason, aerodynamics is a critically important subject for pilots.

Aerodynamics for Aviators is prepared specifically for pilots, by pilots, and its purpose is to present the basic fundamentals of aerodynamics. Many of the basic assumptions and limitations of certain parts of aerodynamic theory have been communicated at the "pilot level." It is not the authors' intention to communicate the principles of aerodynamics at a level of content and complexity for aeronautical engineers or test pilots. If a more detailed investigation into aerodynamic principles is desired, utilize these individuals wherever possible.

The content of *Aerodynamics for Aviators* has been arranged to provide a complete reference for all phases of flying. The text material is applicable to the problems of flight training, transition training, and general flying operations. *Aerodynamics for Aviators* is designed to be used along with a Federal Aviation Administration (FAA) approved Part 141 Pilot School Training Course Outline. The major topics discussed in this textbook mirror the FAA requirements for training a new private pilot, commercial pilot, and future transport category pilot. In studying this text, you should keep in mind practical situations and applications of the aerodynamic principles.

Thrust, drag, lift, and weight are forces that act upon all aircraft in flight. Understanding how the forces of thrust, drag, lift, and weight work and knowing how to control them with the use of power and flight controls are essential skills needed by every pilot. Good luck in your learning, understanding, and appreciation of the aerodynamics of flight.

Symbols & Abbreviations

h	altitude (feet)
Hd	density altitude
P	pressure (lb/ft^2)
T	temperature
ρ	air density (slugs per cu. ft)

1

chapter

The Atmosphere

Introduction

To begin understanding how an airplane flies, a pilot should be familiar with the basic principles of the atmosphere. This chapter explains the composition of the atmosphere, the basics of atmospheric pressure, and water content. These basic principles and physical laws provide the foundation a pilot needs in order to have an understanding of aerodynamics for airplanes.

The atmosphere is a gaseous envelope covering the earth. If the earth were the size of a basketball, the thickness of the atmosphere would be about as thick as a pillowcase wrapped tightly around the ball. Gravity holds the atmosphere to the earth's surface as it rotates. The atmosphere also has motions called circulations that occur relative to the earth's surface. Circulations are caused primarily by the temperature differential that exists between the tropic and the polar regions, and by uneven heating of land and water areas by the sun.

Heavier-than-air flight is dependent upon the aerodynamic force originating from a category of fluids known as gases. The earth's atmosphere is a mixture of gases with traces of water vapor and various other components such as argon and carbon dioxide. The magnitudes of the aerodynamic forces acting on an aircraft are dependent on the shear stress and pressures exerted by the gases that surround it.

Characteristics of the atmosphere such as pressure, temperature, and velocity are used by a pilot to determine whether a flight will achieve adequate performance, or even become airborne. The characteristics of the atmosphere vary with altitude, and each characteristic has a unique effect on weather and many other detailed data points that are also considered in the preparation of flight plans.

Blaise Pascal (1623–1662) and Evangelista Torricelli (1608–1647) have been credited with developing the barometer, an instrument for

Key Terms

absolute humidity
atmospheric pressure
barometer
density altitude
dew point
exosphere
humidity
International Standard Atmosphere
ionosphere
lapse rate
mercury
ozone
pressure altitude
relative humidity
standard datum plane
stratosphere
tropopause
troposphere
U.S. Standard Atmosphere
vapor pressure
water vapor

measuring atmospheric pressure. The results of their experiments are still used today with very little improvement in design or knowledge. They determined that air has weight which changes as altitude is changed with respect to sea level. Today scientists are also interested in how the atmosphere affects the performance of an aircraft and its equipment.

Composition of the Atmosphere

The atmosphere is an envelope of air that surrounds the earth and rests upon its surface. It is as much a part of the earth as the sea or land, but air differs from land and water in that it is a mixture of gases. The atmosphere has mass, weight, and an indefinite shape.

All matter is constructed of atoms, with the configuration of the atom determining the kind of matter present (e.g., oxygen, neon, silver). Individual atoms can combine with other atoms to form molecules. Under normal conditions, matter on Earth exists as a solid, a liquid, or a gas. The atmosphere consists of a mixture of various gases. Dry air is composed of approximately 78 percent nitrogen, 21 percent oxygen, and a 1 percent mixture of other gases, mostly argon (Figure 1-1). Some of these elements are heavier than others. Heavier elements, such as oxygen, settle to the surface of the earth, while lighter elements rise up to the higher-altitude regions. Most of the atmosphere's oxygen is contained below 35,000 feet. Air, like a fluid, is able to flow and change shape when subjected to even minute changes in pressure because it lacks strong molecular cohesion. For example, gas will completely fill any container into which it is placed, expanding or contracting to adjust its shape to the limits of the container.

One of the important components of the atmosphere is **water vapor**, which varies in amounts from 0 to 5 percent by volume. It is present in three physical states: as a gas, liquid, and solid. The maximum amount of gaseous water vapor the air can hold is

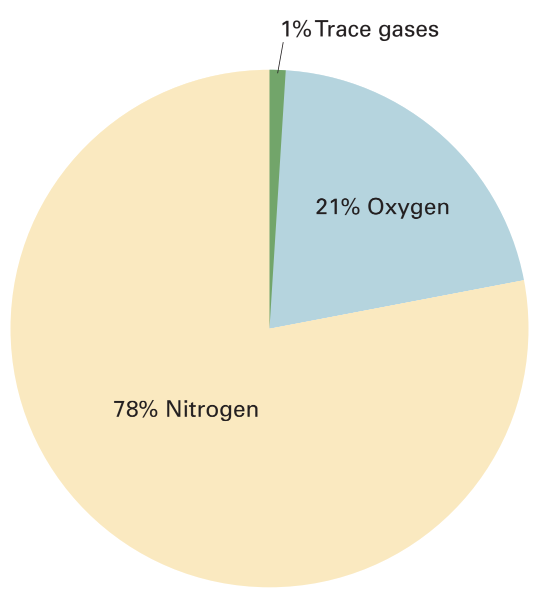


Figure 1-1. Composition of the atmosphere.

temperature-dependent; the higher the temperature, the more water vapor the air can hold. Water vapor remains invisibly suspended in the atmosphere until, through condensation, it grows to sufficient droplet or ice crystal size to form clouds or precipitation.

In addition to a number of gases, the atmosphere also contains variable quantities of foreign matter and impurities such as pollen, dust, bacteria, soot, volcanic ash, spores, salt particles, and dust from outer space—even when the air is apparently clear.

The atmosphere is a complex and ever-changing mixture. Its ingredients vary from place to place and from day to day. The composition of the air remains almost constant from sea level up to its highest level, but its density diminishes rapidly with altitude. Six miles up, for example, the air is too thin to support respiration, and 12 miles up, not enough oxygen is present to support combustion, except in some specially designed turbine engine-powered airplanes.

At a point several hundred miles above the earth, some gas particles spray out into space, some of which are dragged by gravity and fall back into the air below, while others never return. Physicists disagree as to the boundaries of the outer fringes of the atmosphere. Some think it begins 240 miles above the earth and extends to 400 miles; others place its lower edge at 600 miles and its upper boundary at 6,000 miles. Certain nonconformities exist at various levels. Between 12 and 30 miles above the earth, high solar ultraviolet radiation reacts with oxygen molecules to produce a thin curtain of **ozone** (O_3), which is a very poisonous gas—but one without which life on earth could not exist. The ozone layer filters out a portion of the sun's lethal ultraviolet rays, allowing only enough through to give us sunburn, kill bacteria, and prevent rickets.

At 50 to 65 miles up, most of the oxygen molecules begin to break down under solar radiation into free atoms, and form hydroxyl ions (OH) from water vapor. In this region, all the atoms also become ionized.

Studies of the atmosphere have revealed that the temperature does not decrease uniformly with increasing altitude. Instead, it gets steadily colder up to a height of about 7 miles, where the rate of temperature change slows down abruptly and remains almost constant at –55 degrees Centigrade (218 Kelvin) up to about 20 miles. Then the temperature begins to rise to a peak value of 77°C (350 Kelvin) at the 55-mile level. Thereafter, it climbs steadily until reaching 2,270°C (2,543 K) at a height of 250 to 400 miles. From the 50-mile level upward, a human or any other living creature, without the protective cover of the atmosphere, would be broiled on the side facing the sun and frozen on the other.

The atmosphere is divided into four concentric layers or levels: the troposphere, stratosphere, ionosphere, and exosphere. Transition through these layers is gradual and without sharply defined boundaries. However, one boundary, called the tropopause, exists between the first and second layer.

The **troposphere** extends from the earth's surface to about 35,000 feet at middle latitudes, but varies from 28,000 feet at the poles to about 54,000 feet at the equator (Figure 1-2). The troposphere is characterized by large changes in temperature and humidity and by generally turbulent conditions. Nearly all cloud formations are within the troposphere, and approximately three-fourths of the total weight of the atmosphere is within the troposphere. The troposphere is defined by a decrease in temperature with an increase in altitude.

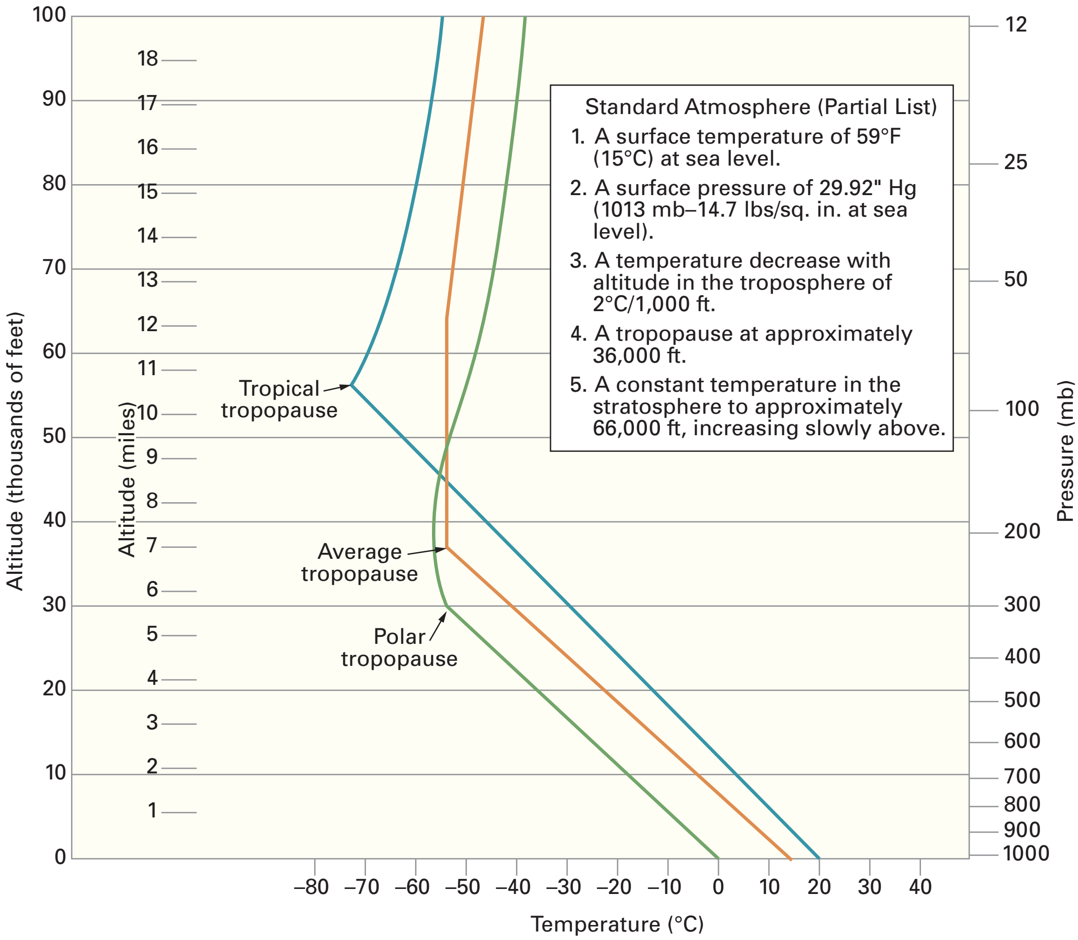


Figure 1-2. The height of the tropopause varies with latitude. (U.S. Airforce)

As a general rule of thumb, localized inversions can cause the temperature to increase with altitude.

The troposphere and stratosphere are separated by the **tropopause**. The tropopause is defined as the point in the atmosphere at which the decrease in temperature (with increasing altitude) abruptly ceases.

The **stratosphere** extends from the upper limits of the troposphere (and the tropopause) to an average altitude of 60 miles. The upper portion of the stratosphere is often called the chemosphere or ozonosphere. The stratosphere is characterized by level temperature and a very stable atmosphere. Because the temperature in the tropopause and lower stratosphere remains constant (or slightly decreases) with increasing altitude, very little convective turbulence occurs at these altitudes. Though most turbulence at this altitude is caused by variations in the jet stream and other local wind shears, areas of significant convective activity (thunderstorms) occur below the stratosphere, in the troposphere.

The **ionosphere** ranges from the 50-mile level to a level of 300 to 600 miles. Little is known about the characteristics of the ionosphere, but it is thought that many electrical phenomena occur there. Basically, this layer is characterized by the presence of ions and free electrons, and the ionization seems to increase with altitude and in successive layers. The **exosphere** is the outer layer of the atmosphere. It begins at an altitude of 600 miles and extends to the limits of the atmosphere. In this layer, the temperature is fairly constant at 2,500 K, and propagation of sound is thought to be impossible due to lack of molecular substance.

Water Content of the Atmosphere

In the troposphere, the air is rarely completely dry. It contains water content in one of two forms: fog or water vapor. Fog consists of minute droplets of water held in suspension by the air. Clouds are composed of fog. The height to which some clouds extend is a good indication of the presence of water in the atmosphere almost up to the stratosphere.

As a result of evaporation, the atmosphere always contains some moisture in the form of water vapor. The moisture in the air is called the humidity of the air. Moisture does not consist of tiny particles of liquid held in suspension in the air as in the case of fog, but consists of an invisible vapor truly as gaseous as the air with which it mixes.

Effect on Performance

Fog and humidity both affect the performance of an aircraft. In flight, at cruising power, the effects are small and receive no consideration. During takeoff, however, humidity has important effects. Two things are done to compensate for the effects of humidity on takeoff performance. Since humid air is less dense than dry air, the allowable takeoff gross weight of an aircraft is generally reduced for operation in areas that are consistently humid. Second, because the power output of reciprocating engines is decreased by humidity, the manifold pressure may need to be increased above that recommended for takeoff in dry air in order to obtain the same power output.

Engine power output is calculated on dry air. Since water vapor is incombustible, its pressure in the atmosphere is a total loss as far as contributing to power output. The mixture of water vapor and air is drawn through the carburetor, and fuel is metered into it as though it were all air. This mixture of water vapor, air, and fuel enters the combustion chamber where it is ignited. Since the water vapor will not burn, the effective fuel/air ratio is enriched and the engine operates as though it were on an excessively rich mixture. The resulting horsepower loss under humid conditions can therefore be attributed to the loss in volumetric efficiency due to displaced air, and the incomplete combustion due to an excessively rich fuel–air mixture.

The reduction in power that can be expected from humidity is usually given in charts in the flight manual. There are several types of charts in use. Some merely show the expected reduction in power due to humidity; others show the boost in manifold pressure necessary to restore full takeoff power. The effect of fog on the performance of an engine is very noticeable, particularly on engines with high compression ratios. Normally, some detonation will occur during acceleration, due to the high BMEP (brake mean effective pressures)

Aerodynamics *for Aviators*

SECOND EDITION

Mark Dusenbury
Gary Ullrich
Shelby Balogh

Authors Gary Ullrich and Mark Dusenbury are University of North Dakota professors with extensive experience as military and civilian pilots, and instructors. Shelby Balogh is a data and analytics scientist at GE Aviation.

Aerodynamics for Aviators is a collegiate-level aerodynamics textbook that covers all of the necessary information relevant to pilots, from the private license through to the commercial. Aerodynamics is a subject critical to pilots' understanding of the safe maneuvering and operation of aircraft. This textbook takes the student through a basic physical principles review and vector analysis before covering the four forces in flight. Sections are dedicated to subsonic aerodynamics as well as high-speed (transonic) aerodynamics.

Lift, weight, thrust, and drag are examined in a logical and detailed manner. In addition, this comprehensive and detailed resource covers the atmosphere, stability, power and performance, limitations and maneuvering flight, and stalls and spins. Subjects are explored both conceptually as well as mathematically for maximum understanding. Each chapter contains key terms, symbols and abbreviations, review questions, and full-color illustrations. The appendices provide additional useful resources, including a math and physics review, glossary, and aerodynamic equations.

Aviation Supplies & Academics, Inc.
7005 132nd Place SE
Newcastle, Washington 98059
800-ASA-2-FLY
www.asa2fly.com

ASA-AERODYN-2

TRANSPORTATION USD $49.95

ISBN 978-1-61954-333-1

54995 >

9 781619 543331